Fermi National Accelerator Laboratory

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Conceptual Design Report for a Superconducting Coil Suitable for Use in the Large Solenoid Detector at the SSC*

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CONCEPTUAL DESIGN REPORT FOR A SUPERCONDUCTING COIL SUITABLE FOR USE IN THE LARGE SOLENOID DETECTOR AT THE SSC

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ABSTRACT

The conceptual design of a large superconducting solenoid suitable for a magnetic detector at the Superconducting Super Collider (SSC) was done at Fermilab. The magnet will provide a magnetic field of 1.7 T over a volume 8 m in diameter by 16 m long. The particle-physics calorimetry will be inside the field volume and so the coil will be bath cooled and cryostable; the vessels will be stainless steel. Predictibility of performance and the ability to safely negotiate all probable failure modes, including a quench, are important items of the design philosophy. Our conceptual design of the magnet and calorimeter has convinced us that this magnet is a reasonable extrapolation of present technology and is therefore feasible. The principle difficulties anticipated are those associated the the very large physical dimensions and stored energy of the magnet.

INTRODUCTION

A large solenoid is being considered as part of a detector for an experiment to be performed on the Superconducting Super Collider (SSC). The conceptual design of a solenoid suitable for such a detector was done at Fermilab and some preliminary specifications have been developed. Some of the requirements placed on the SSC detector magnet by the nature of 20 TeV proton-proton interactions are similar to those for other large diameter solenoids found at high-energy physics laboratories around the world, but others are remarkably different. One significant difference in the detector is that, unlike collider detectors for LEP at CERN and the Tevatron at Fermilab, both electromagnetic and hadronic calorimetry for the SSC detector will be inside the bore of the magnet. As a result, the coil and cryostat do not have to be "thin" in terms of radiation or absorption lengths. We have chosen to adopt a bath-cooled, cryostable coil design and to use stainless steel rather than aluminum for the helium and vacuum vessels. We believe that these choices will contribute greatly to the reliability and predictability of the magnet system.

Our magnet design provides a magnetic field of 1.7 T over a cylindrical volume 8 m in diameter and 16 m long. An iron yoke will reduce the excitation required and will assist in providing muon identification and a redundant momentum measurement of the muons. The stored energy in the magnetic field is 1.4 GJ.

The calorimeter and central tracking chamber for the detector will occupy a volume 8 m in diameter by 16 m and will weigh about 5000 metric tonnes. This weight could be transmitted to the floor of the detector hall either through the vacuum vessel of the magnet cryostat or through an independent support structure. The calorimeter would be split at the longitudinal center for supports to minimize lost pseudorapidity coverage by the tracking and calorimetry. We have decided on two independent calorimetry support structures each 8 m long--the trussed cylinder shown in Fig. 1. This structure is a stainless steel weldment with a radial thickness of 250 mm. The cylinders are 38 mm thick, while the truss web is made of 12 mm plates. The deflection of the structure when loaded with the calorimeter modules was calculated with a finite element analysis to be about 30 mm; it would be attached to the iron yoke at both ends. The calorimeter modules would rest on rails along each side of the truss structure and could be installed from either or both ends.

We have adopted a fabrication and assembly plan in which eight 2-m long coil and vacuum vessel modules are fabricated and individually tested with liquid helium. These modules are then assembled into two 8-m cryostats, each with a liquid helium storage dewar. These coil-cryostat assemblies are then lowered into the experimental hall and mounted to the iron yoke.

A more detailed scenario for this plan is: (1) The coil is wound in 2-m long modules about a vertical axis, and each module closed to form a liquid helium vessel. (2) The coil-helium vessel module is installed inside a 2-m outer vacuum vessel module, with liquid nitrogen cooled thermal shield attached, by a temporary support system. (3) The vacuum vessel is then closed with a temporary inner vacuum shell and annular heads.

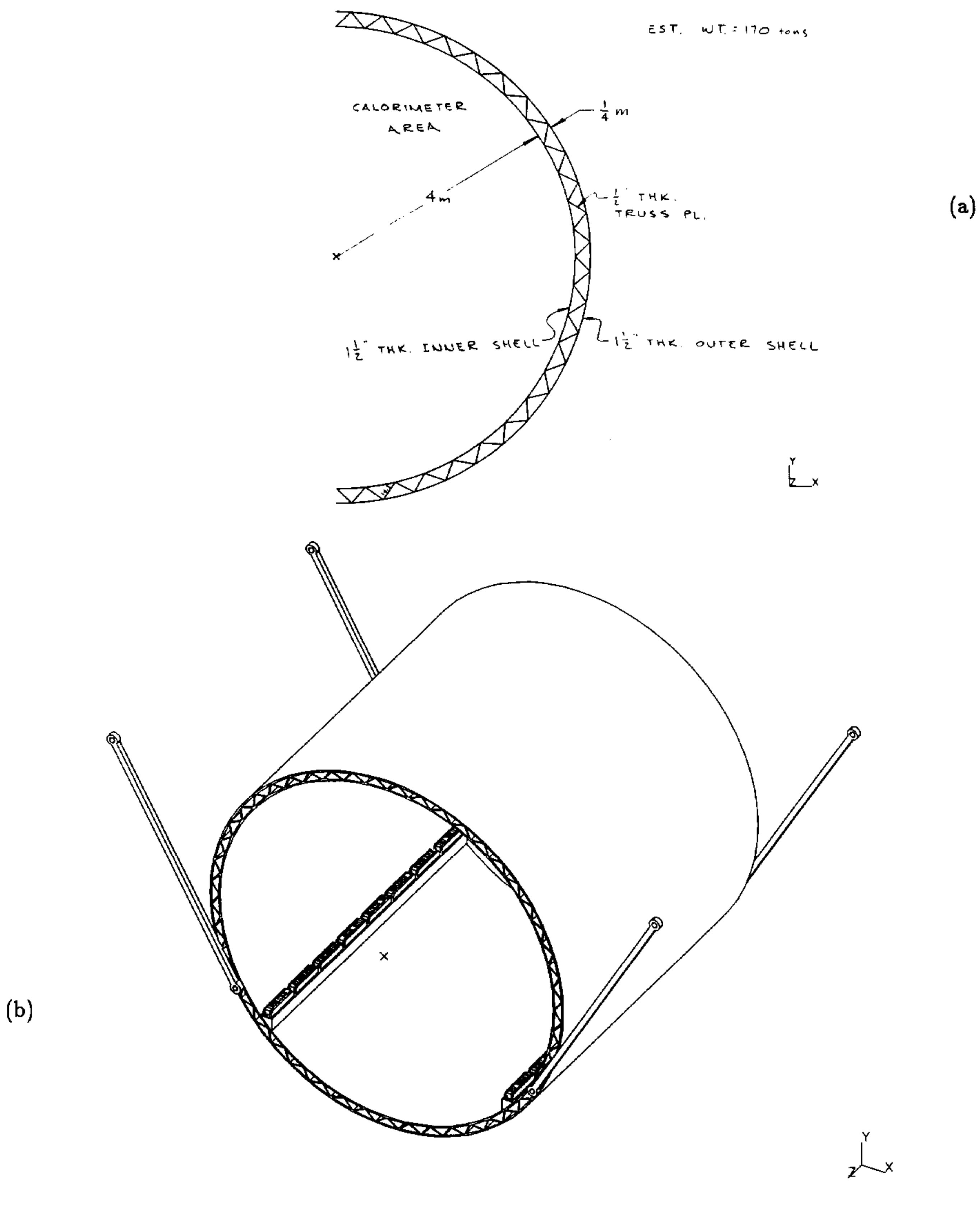


Fig. 1. Calorimeter support structure. (a) cross section geometry, (b) structure with module rails and Hillman rollers and support arms to iron yoke.

(4) The current lead chimney is completed and the cryogenic lines connected to a temporary supply of liquid nitrogen and helium. (5) The 2-m module is cooled, filled with liquid helium, and tested to an appropriate current. (6) Four coil-outer vacuum shell modules are assembled and bolted together to form an 8-m cold mass supported in an 8-m outer vacuum shell with a radial-axial separated-function support system. (7) The inner vacuum shell and thermal shield are inserted and the closure welds made. (8) The helium storage dewar and connecting piping are then attached to this 8-m cryostat assembly. (9) The two 8-m assemblies could be cryogenically and electrically tested at this point. (10) These finished 8-m assemblies, each weighing about 800 metric tonnes, are lowered into the underground detector hall and secured to the iron yoke in a way that allows for a 20^{o}C thermal contraction of the 8-m vacuum vessel. Figure 2 shows an 8-m assembly.

The parameters adopted for this conceptual design report are given in Appendix A. Backup calculations related to conductor sizing, quench behavior, coil charging and discharging are given in Appendix B. We realize that further, more detailed calculations and reliability-cost optimizations will probably result in final design parameters somewhat different from these. However, we believe that these, usually conservative, parameters are useful in determining the engineering feasibility of the magnet.

QUENCH PROTECTION AND CONDUCTOR SPECIFICATION

In order to accomodate a calorimeter 8 m in diameter, the inner diameter of the inner vacuum shell is 8.9 m. Cryostat shell thicknesses, the radiation shield, insulating vacuum space and electrical insulation occupy 337 mm (13.5 in) so the inner diameter of the first layer of the superconducting coil is 9.574 m. To reduce the liquefaction

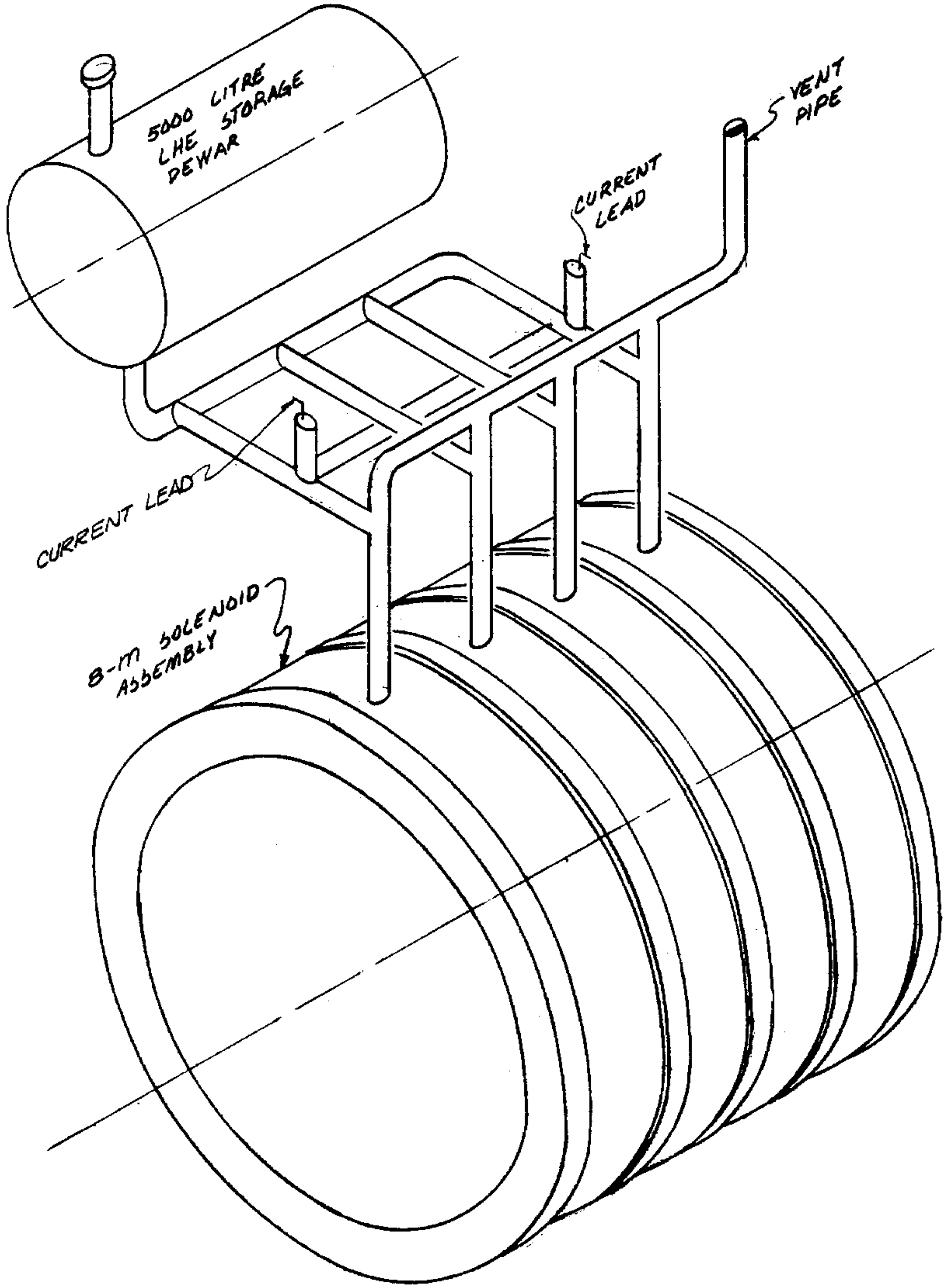


Fig. 2. Eight-meter assembly.

demand on the helium system, we chose an operating current of 5 kA. All eight 2-m coil modules are connected in series electrically so that the same current flows in each. Each 2-m coil module has a pair of gas-cooled current leads which will be used for testing the module. The current lead chimneys will permit four 2-m coil modules to be connected in series with superconducting bus in liquid helium. We believe that it is essential that the coil survive a 5-kA quench without damage. We have chosen to provide this protection through the use of an external 0.1 Ω fast discharge resistor and by specifying a conductor current density consistent with an adiabatic maximum hot spot temperature following a quench of 90 K. The current density was calculated with the simplistic, very conservative heat balance method:

$$J_0^2 L/R = 2 \int_{\theta 0}^{\theta m} \gamma C(\theta)/\rho(\theta)\ d\theta$$

where J_0 = conductor (copper) current density at the operating current

L = coil inductance = 112 H

R = fast discharge resistor = 0.1 Ω

L/R = maximum fast discharge time constant = 1120 s

γ = conductor (copper) density [kg/m^3]

$C(\theta)$ = conductor (copper) specific heat [J/kg-K]

$\rho(\theta)$ = conductor (copper) resistivity [Ω-m]

$\theta 0$ = superconducting-normal transition temperature = 10 K

θm = adiabatic maximum hot spot temperature

With θm = 90 K and copper with RRR = 100, $J_0 = 1.07 \times 10^7$ A/m^2 = 10.7 A/mm^2.

The conductor for the magnet will be built up with a Nb-Ti/Cu monolith or cable soldered into additional copper stabilizer. The dimensions of the conductor for all eight coil modules are 16 mm x 18 mm, a current density at 5 kA of 10.7 A/mm^2. The specified short sample rating at 4.5 K and 2 T is 10 kA. With a current density in the superconductor of 3×10^9 A/m^2, the copper to superconductor area ratio will be about 140. The full surface heat flux at 5 kA with a copper resistivity of 1.55×10^{-10} Ω-m is 9.4 mW/cm^2. The operating current is 61% of short sample along the load line, a temperature margin of about 2.2 K. About 150 km, 92 miles, of conductor, weighing about 625 tonnes, is required for the magnet.

Normal discharge will be through a slow discharge resistor, with the power supply reversed so the discharge is at constant voltage. Eddy current heating during a slow discharge is less than 100 W. There is, however, a significant heat load due to eddy current in the coil and helium vessel during a fast discharge, with peak or initial values approximately 700 W in the coil modules and 1500 W in the helium vessels. Since the modules are in series electrically, the current will decay the same way in all modules. However, this eddy current heat load could initiate a more or less simultaneous quench in each module in the event of a fast discharge. A fast discharge will therefore be initiated only when a quench is detected. A simplified electrical schematic of the magnet system is shown in Fig. 3.

DESIGN OF THE COIL-HELIUM VESSEL MODULE

Magnetostatic calculations showed that a central field of 1.7 T could be achieved if each of the eight coil modules provided an excitation of 2.81 megampere-turns. We designed each 2-m coil module to have seven layers of 88 turns for a total of 616 turns. At 5 kA this provides 3.08 MAt, about 10% more than the calculation indicated were necessary, a safety factor necessary because of uncertainties in the calculation.

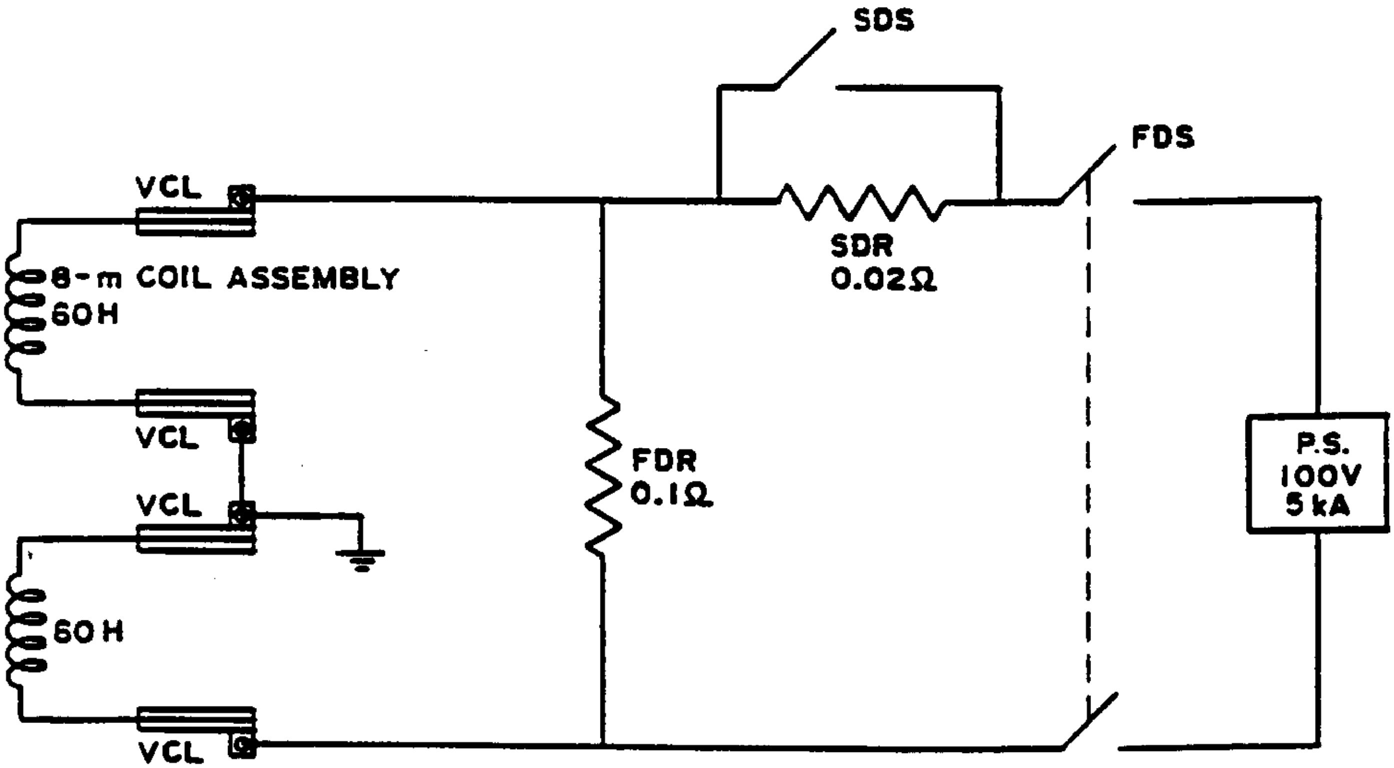


Fig. 3. Electrical schematic: FDR, fast discharge resistor; FDS, fast discharge switch (normally closed, opened to initiate a fast discharge); SDR, slow discharge resistor; SDS, slow discharge switch (normally closed, opened to initiate a slow discharge); VCL, vapor cooled leads; P.S., power supply

We chose 2.62-mm G-10 buttons on a string as the turn-to-turn insulation and 5-mm slotted G-10 sheets between layers. The ground insulation is 75 mm of slotted and channeled G-10 and Kapton.

The conductor is layer wound the "hard" way, beginning at the outside, or eighth layer, on a coil form made up of the outer shell and annular flat heads of the helium vessel. We visualize the coil form to be stationary with a vertical axis of rotation. The winding fixture carries a conductor spool, a reel of turn-to-turn insulation, and cleaning and insulation applying equipment. It rotates in a horizontal plane and traverses the vertical axis, applying a radial preload. Compression bars at the ends of the coil apply an axial preload to each layer as it is wound. The lead-in bus enters and exits the coil pack through channels in the ground insulation. We hope that the conductor can be procured in about 2.5-km lengths so that the only splices are between layers.

Figure 4 is a cut-away view of the coil. The coil module will be closed by welding the inner shell, modularized circumferentially, to the coil form. The lead-in bus passes out the chimney of the module, which also serves as the return flow pipe and the quench vent.

The 2-m coil-helium vessel module was designed in accordance with the *Boiler and Pressure Vessel Code* of the American Society of Mechanical Engineers (ASME). The vessel was designed to be evacuated and for an internal gauge pressure of 0.7 MPa (100 psig). The outward radial design pressure of the outer shell was 1.2 MPa (175 psig) to permit the shell to react a portion of the radial electromagnetic pressure. The inner and outer shell thicknesses are adequate to carry the axial electromagnetic force from the coils to the axial supports.

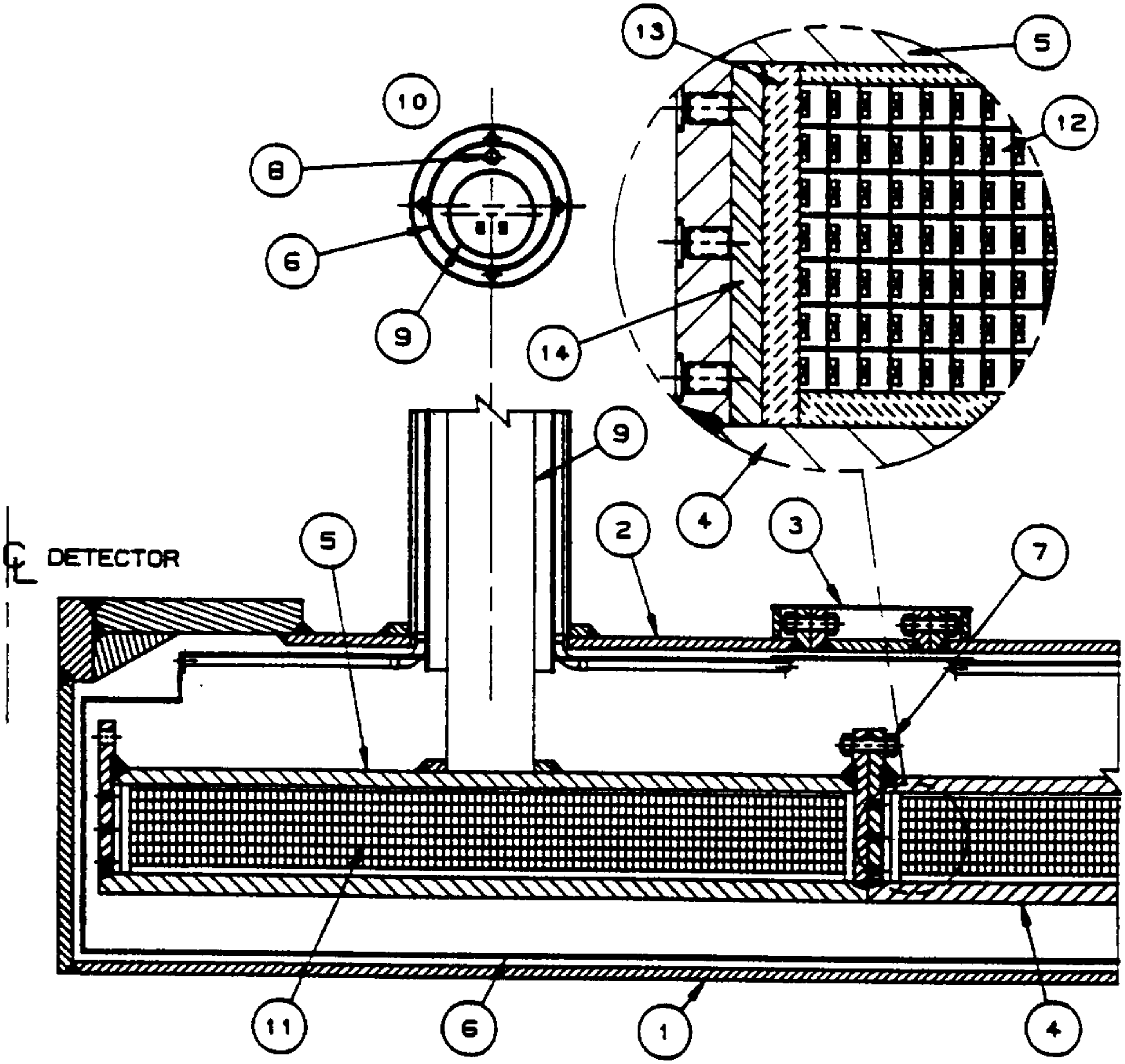


Fig. 4. Axial cross section of coil, helium and vacuum vessels: 1, inner and 2, outer vacuum shells; 3, assembly joint (if required); 4, inner and 5, outer helium vessel shell; 6, radiation shield; 7, coil module attachment; 8, liquid helium supply pipe; 9, helium return/vent pipe; 10, chimney to storage dewar; 11, coil winding; 12, conductor; 13, insulation; 14, axial preload bar.

We have not considered in depth the question of tolerances on the coil-helium vessel module. We have, however, provided generous vacuum spaces on either side of the module (100 mm on the inside, 300 mm on the outside) to accomodate the out-of-roundness of the modules and vacuum shells.

We propose to use a thermosiphon, as was used on the Aleph solenoid at LEP and the Mirror Fusion Test Facility solenoids at Livermore, to provide a flow of liquid helium through the coil package. Each of the coil-helium vessel modules will have a separate line from the storage dewar to supply helium which is 100% liquid to the bottom of the module.

DESIGN OF THE RADIATION SHIELDS

Liquid nitrogen cooled shields will reduce the radiation heat transfer from the vacuum vessel to the liquid helium system. The shields will be mounted to the inner and outer vacuum shells with low conductivity supports which allow the shields to contract when cooled. The shields are made of either copper or aluminum sheets with a cooling tube attached. The size of the cooling tube and the number of parallel circuits are determined by the 0.13 MPa (19 psi) pressure difference available from the subcooled liquid nitrogen circulating system.

A flow of subcooled liquid nitrogen will be maintained through the series-parallel circuit. The pressure and temperature of the liquid entering the magnet are 6 atmospheres and 77.5 K; the liquid leaves the magnet at 4.7 atmospheres and 89 K.

DESIGN OF THE SUPPORT SYSTEM

Four coil modules are connected together forming one 8-m cold mass to be supported inside each 8-m vacuum vessel. The support system could have been either combined function, where the load bearing members support both the axial and radial components of the total body force, or separated function with two types of members, one to support the axial component and another to support the radial component. The combined function style is attractive because by properly adjusting the angle between the support and the axis the force due to thermal contraction can be eliminated. However since the supports are at this angle a large buckling force is generated when reacting the axial decentering force. A separated function system with radial and axial members does not have this disadvantage and we have therefore chosen it. Another advantage of a radial-axial system is that the members can be much longer, which greatly reduces the conduction heat load to the helium system. The support system provides axial stiffness by using a number of axial members, either 24 or 48, located at intervals around the outer circumference of the cold mass. Radial stiffness is provided by a set of approximately tangential members, in a plane normal to the axis, around the circumference at each end of the 8-m cold mass.

We have decided that the support system should be adequate to permit operation of the magnet with one of the eight coils at zero current. This will allow the magnet and the detector to be operated, but at reduced field, should one of the coil modules fail. This could be important since it will be necessary to completely disassemble the detector to repair or replace a failed coil module.

We have also decided that for reliability the support members should be metallic, probably Inconel 718, and designed with an appropriate safety factor. We used the *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings* of the American Institute of Steel Construction (AISC) as the source of allowable stress and column loading formulae. Each support member has spherical bearings on each end.

The 2-m coil-helium vessel modules will have temporary supports installed for testing. These supports will be removed when the coil modules are connected together to form the 8-m cold mass.

The warm ends of all support members will be attached near the ends of the vacuum vessels to avoid transmitting the electromagnetic loads and the weight through the vacuum shells. The cold ends of both the axial and the radial members are attached to the cold mass on its outer diameter. Each support member has two heat intercepts, one cooled by liquid nitrogen and another in the cold-end attachment block in a liquid helium thermosiphon circuit.

CALCULATION OF MAGNETOSTATIC FIELDS AND FORCES

The general purpose finite element program ANSYS (copyright Swanson Analysis Systems, Inc.), with two- and three-dimensional magnetostatic capabilities, was used to calculate the magnetic field, Lorentz forces, and the stored energy for different coil and iron geometries. Initial calculations were done assuming steel of infinite permeability; the final results are with finite permeability. The computational results are summarized in Appendix A, while the method and the details are given in Appendix D. A two-dimensional axisymetric model was found to be adequate for much of the analysis, but a three-dimensional model was used to compute the radial decentering force.

Figure 5 shows the value of the axial field component as a function of z with r = 0, $B_z(0,z)$, with each of the eight coils energized to 2.81 MAt and with one of the coil modules deenergized.

When installed on the iron yoke, each 8-m cold mass has an axial body force on it which depends on the gap between the coil and the iron end wall and on the amount of re-entrant iron in the end plug. For a given set of coil-to-coil spacings and with all eight coils equally energized this force can be theoretically eliminated by the proper choice of end wall and plug geometry. In our case, with intercoil gaps of 138 mm, a midplane gap of 568 mm and 2.81 MAt per coil, the axial force on each 8-m cold mass was calculated to be negligible if the coil-to-iron gap was 300 mm and if there was no

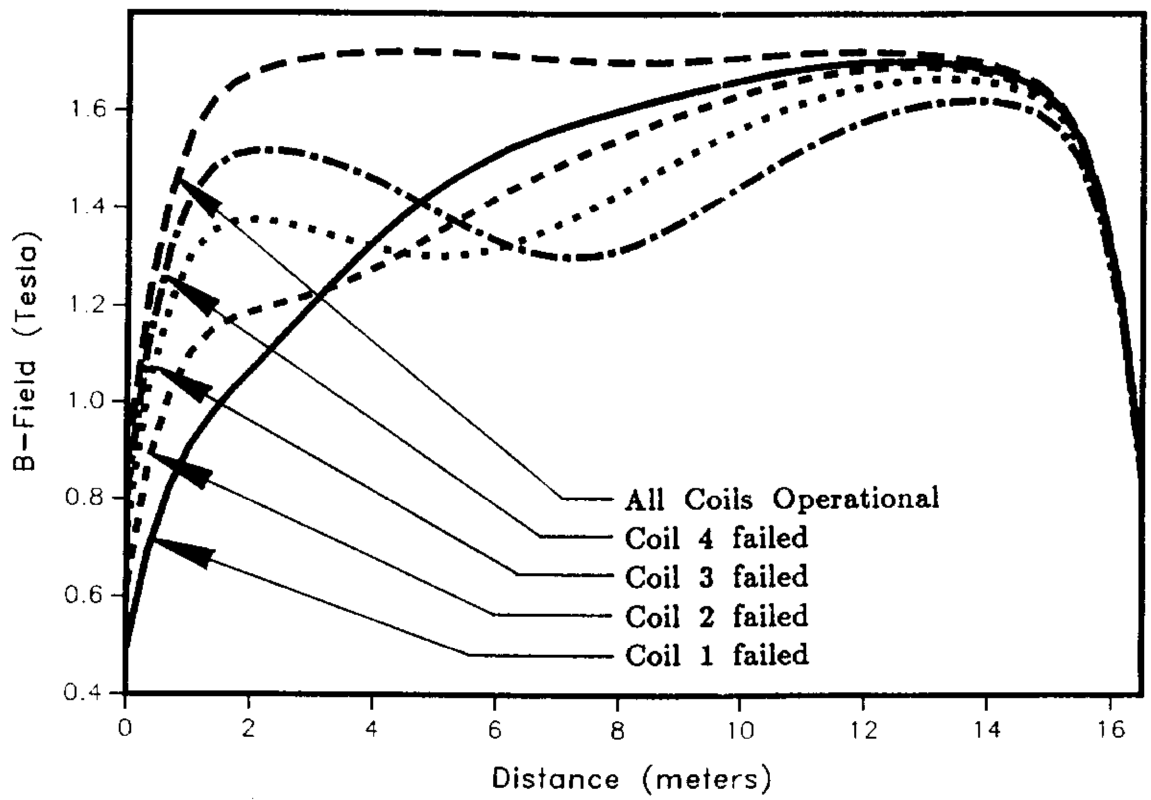


Fig. 5. Field on solenoid axis for various coil failure scenarios. Coil 1 is the outermost coil, coil 4 is nearest the axial mid-plane.

re-entrant iron in the end plug. With one of the coils deenergized there is an axial force on the cold mass which depends on which coil is deenergized. Table 2 in Appendix D gives this force for different deenergized coils, with the other seven at full excitation. The maximum value of this axial force, 54.2 MN, about 12 million pounds, occurs with the outermost coil module deenergized. The axial support system is accordingly designed for a force of 54.2 MN (12 Mlbf).

There are five ways that the two 8-m cold masses can be axially decentered with respect to each other and the steel yoke. We calculated the axial force on each 8-m cold mass for these decentering cases with all eight coils equally energized. The maximum force will occur when both 8-m cold masses are displaced toward the midplane. The radial decentering force constant is 8 kN/mm (45,600 lbf/in). From experience with the solenoid at the CDF at Fermilab we have chosen an axial and radial misalignment or the equivalent, due to non-uniform iron properties, of 25 mm. This results in an axial decentering force of 12.4 MN (2.8 Mlbf), which is much less than the design specification of the axial support system. The radial decentering force with a 25-mm misalignment is 0.2 MN (45,000 lbf), which is also much less than the 8-m cold mass (664 tonnes, 1.46 Mlbf) to which the radial support system is designed.

LIQUID HELIUM STORAGE DEWAR

A horizontal, 5000 L liquid helium storage dewar, located above the iron yoke, is connected to the four coil-helium vessel modules in each 8-m assembly through a chimney manifold as shown in Fig. 2. This manifold contains four gas-cooled current leads and has the provision for connecting the current leads in series in liquid helium. A vent pipe to relieve the individual modules in the event of a quench or loss of insulating vacuum is part of the interconnect manifold. The liquid vessel is designed in accordance with the ASME *Boiler and Pressure Vessel Code* for a gauge pressure 0.7 MPa (100 psig).

MANUFACTURING, ASSEMBLY, AND TESTING CONSIDERATIONS

The size and weight of the 8-m solenoid assemblies will preclude its fabrication and assembly at a vendor's off-site facility. A preliminary inquiry (Appendix D) indicates that a 2-m coil-helium vessel module or even a completed 2-m module could be fabricated elsewhere and transported to the Waxahatchie site by barge and truck. It is unclear whether the cryogenic testing of the 2-m modules would take place at a vendor's facility or on site. A large hall will be provided on the SSC site for the assembly and cryogenic testing of the 8-m modules. The hall will require at least a 200 tonne crane with a hook height of at least 12 m. The access shaft from the surface to the detector hall will be about 14 m in diameter.

REFRIGERATION SYSTEM

The refrigeration plant will be located at ground level, while the magnet will be about 50 m below ground on the Texas SSC site. The plant will supply liquid helium to the two storage dewars atop the detector. A cold compressor will be used if necessary to maintain the liquid in the dewars at about 30 kPa and 4.5 K. Sub-cooled liquid nitrogen will be forced through the various shield and intercept circuits by a circulator pump at detector hall level.

The cold mass of each 8-m assembly is about 650 tonnes; a cooldown time of about two weeks is desirable. Energy must be extracted at an average rate of about 50 kW to cool down an 8-m assembly in 300 h. It is likely that a separate cooldown refrigerator will be used.

The parameters of the refrigeration system are given in Appendix E.

CONCLUSION

We concluded, as a result of this preliminary study, that the magnet is a reasonable extrapolation of superconducting magnet technology. The optimization of parameters through more detailed study might result in a more cost-effective design, but we believe we have established the feasibility of the magnet.

APPENDIXES

Appendix A: Solenoid Parameters and Dimensions

GENERAL	
Overall inner diameter	8.900 m, 29.20 ft, 350.4 in
Overall outer diameter	11.272 m, 36.98 ft, 443.7 in
Radial thickness	1.186 m, 3.89 ft, 46.7 in
Overall length	16.250 m, 53.31 ft, 639.8 in
Design operating central field	1.7 T
Stored energy at 1.7 T	1400 MJ
Total weight of coils and cryostats	~ 1600 tonnes (metric tons)
COIL	
Number of coil modules	8
Nominal length of coil module	2 m
Active length of coil module	1.812 m, 5.94 ft, 71.34 in
Calculated excitation per module for 1.7 T	2.81 MAt (same for all 8)
Maximum operating current	5 kA
Turns per module	616
Turns per layer	88
Layers per module	7
Excitation available per module	3.08 MAt at 5 kA
Total self inductance	112 H
Ground insulation on ID	75 mm, 2.953 in, G-10
Ground insulation on OD	75 mm, 2.953 in, G-10
Turn-to-turn insulation	2.62 mm, 0.103 in, G-10 buttons on string
Layer-to-layer insulation	5 mm, 0.197 in, slotted G-10
Approximate length of conductor per module	18.4 km, 11.5 miles
Approximate total length of conductor	147 km, 92 miles

CONDUCTOR

General	Cu/Nb-Ti cable, soldered to additional copper
Overall dimensions	18 mm x 26 mm, 0.71 in x 1.02 in
Peak field at conductor	1.8 T
Short sample current specification	10 kA, 3×10^9 A/m^2 at 4.5 K and 2 T
Cu:SC area ratio	~140
Conductor (~copper) current density at 5 kA	1.07×10^7 A/m^2 ~ 11 A/mm^2
Specification of stabilizer copper	CDA 101, ASTM B170-1
Copper RRR, completed coil, 2 T	100
Copper resistivity at 4.5 K & 2 T	1.55×10^{-10} Ω-m
Full surface heat flux at 5 kA	9.4 mW/cm^2
Critical current margin	1.1
Critical field margin	1.94
Cryostable current margin	4.48
Fraction of short sample along load line	0.611
Temperature margin	2.26 K

QUENCHING

Fast discharge resistor	0.10 Ω
Nominal fast discharge time constant (inductance/fast discharge resistance)	1120 s
$_0\int^\infty J^2(t)\ dt \sim (0.5)J_0{}^2L/R$	6.41×10^{16} A^2-s-m^{-4}
$_0\int^\infty I^2(t)\ dt$	~14000×10^6, 14000 MIITS
Maximum hot spot temperature	90 K
Initial (max.) eddy current heating in coil during fast discharge	697 W (8 modules)
Energy deposited in coil during fast discharge	390 kJ (8 modules)

Initial (max.) eddy current heating in helium vessel during fast discharge	1481 W (8 modules)
Total inital eddy current heating	2178 W
Energy deposited in helium vessel during fast discharge	829 kJ (8 modules)
Total energy deposited in liquid helium during fast discharge	1219 kJ
Liquid helium boiled during fast discharge	475 L

CHARGING AND SLOW DISCHARGING

Power supply voltage	100 V
Constant voltage charge rate	0.893 A/s
Charge time with constant voltage	93 min
Slow dump resistor	0.02 Ω
Slow discharge time constant	5600 s
Exponential slow discharge time, 5 - 3.75 kA	1600 s
Linear slow discharge time, 3.75 - 0 kA	5600 s
Total slow discharge time from 5 kA	7200 s, 2 h
Eddy current heating--100-V charge--8 modules	87 W, 488 kJ, 190 L LHe
Eddy current heating--slow discharge--8 modules	87 W-max, 381 kJ, 150 L LHe

ELECTROMAGNETIC FORCES WITH IRON YOKE

With all 8 coils energized to 1.7 T, 2.81 MAt	
Axial force on 8-m cold mass	Negligible
Max axial compressive force in 2-m coil module	13.3 MN, 3 Mlbf
Max radial pressure	1.16 MPa, 168 psi
Max axial stress in conductor	2 MPa, ~ 300 psi
Max axial decentering force, with 25 mm axial offset	12.4 MN, 2.8 Mlbf
Radial force constant	8 kN/mm, 45.6 klbf/in

With 7 coils energized to 2.81 MAt, one coil deenergized

Max. axial force on 8-m cold mass	54.2 MN, 12.2 Mlbf
Specification for axial support system	54.2 MN, 12.2 Mlbf
Specification of radial support system	0.2 MN, 45 klbf in any direction plus 664 tonnes, 1.46 Mlbf cold mass

ELECTROMAGNETIC FORCES WITHOUT IRON YOKE

Max. testing current (current giving axial conductor stress equal to maximum with eight coils)	4.06 kA

DIMENSIONS OF COIL-CRYOSTAT-VACUUM VESSEL

Radial dimensions

Inner vacuum shell, ID	8.900 m, 29.20 ft, 350.4 in
Inner vacuum shell, OD	8.958 m, 29.39 ft, 352.7 in
Inner vacuum shell thickness	29 mm, 1.142 in
Inner radiation shield, OD	9.108 m, 29.88 ft, 358.6 in
Inner radiation shield thickness	1 mm, 0.039 in
Inner LHe shell, ID	9.308 m, 30.54 ft, 366.5 in
Inner LHe shell, OD	9.424 m, 30.92 ft, 371.0 in
Inner LHe shell thickness	58 mm, 2.283 in
Inner ground insulation thickness	75 mm, 2.953 in
First conductor layer, ID	9.574 m, 31.41 ft, 376.9 in
Layer insulation thickness	5 mm, 0.197 in
Last (eighth) conductor layer, OD	9.998 m, 32.80 ft, 393.6 in
Outer ground insulation thickness	75 mm, 2.953 in
Outer LHe shell, ID	10.148 m, 33.29 ft, 399.5 in
Outer LHe shell, OD	10.288 m, 33.75 ft, 405.0 in
Outer LHe shell thickness	70 mm, 2.756 in
Outer radiation shield, OD	10.888 m, 35.72 ft, 428.7 in

Outer radiation shield thickness	1 mm, 0.039 in
Outer vacuum shell, ID	11.038 m, 36.21 ft, 434.6 in
Outer vacuum shell, OD	11.102 m, 36.42 ft, 437.1 in
Outer vacuum shell thickness	32 mm, 1.260 in
Module interconnection region, OD	11.272 m, 36.98 ft, 443.8 in
Axial dimensions	
Vacuum vessel, overall length	8.000 m, 26.25 ft, 315.0 in
Vacuum vessel annular head thickness	35 mm, 1.378 in
2-m module, outside length	1.950 m, 6.40 ft, 76.8 in
2-m module annular head thickness	35 mm, 1.378 in
2-m module inside length	1.880 m, 6.17 ft, 74.0 in
Push bar thickness	20 mm, 0.787 in
Ground insulation thickness	24 mm, 0.945 in
Turn-to-turn insulation thickness	2.62 mm, 0.103 in
2-m coil length, conductor-to-conductor	1.812 m, 5.945 ft, 71.34 in
Intercoil gap, conductor-to-conductor	138 mm, 5.433 in
Midplane gap, conductor-to-conductor	568 mm, 22.36 in
Yoke gap, conductor-to-iron	300 mm, 11.8 in

CALCULATED WEIGHTS

2-m coil module, cold mass	
Coil form (outer LHe vessel shell and annular heads)	42.27 tonnes
Axial push bars	0.65 tonnes
Insulation	19.11 tonnes
Conductor	78.00 tonnes
Inner LHe vessel shell	25.88 tonnes
Total module cold mass	165.91 tonnes

2-m vacuum module	
Radiation shields	1.22 tonnes
Outer shell	16.88 tonnes
Total 2-m coil and vacuum module	184.01 tonnes
Inner vacuum shell (8 m)	50.61 tonnes
Vacuum vessel annular flat heads	20.46 tonnes
Total 8-m assembly, w/o support system, storage dewar and interconnecting piping	807 tonnes

Appendix B: Backup Calculations for Parameters in Appendix A

SUMMARY: This appendix contains preliminary calculations, references, and remarks backing up some of the numbers cited in Appendix A.

COIL

1. Active length of coil module

   l_{2m} = 1812 mm, from Jim Krebs

2. Calculated excitation per module for 1.7 T

   From Bob Wands, module current density

   $J_{coil} = 7.312\ \text{MA/m}^2$ for $B(0,0) = 1.7$ T

   $NI(\text{calc, 2 m, 1.7 T}) = J_{coil}\ l_{2m}\ \Delta R = (7.312\ \text{MA/m}^2)(1.812\ \text{m})(0.212\ \text{m})$

   $= 2.81$ MAturns

3. Maximum operating current

   If the as-wound coils all contain the number of turns specified below, the calculated excitation will be attained with 4.56 kA. The power supply will be capable of 5 kA and therefore ~10% extra amp-turns. All conductor, stability and quench issues will be calculated at 5 kA.

4. Turns, turns per layer, layers

   Total of 616 turns, 88 turns/layer x 7 layers, to provide the calculated excitation at 4.56 kA.

5. Excitation available per coil module

   NI(available) = 616 turns x 5 kA = 3.08 MAturns

6. Total self inductance

   $L(16\ \text{m}) = 2E/I^2 = (2)(1400\ \text{MJ})/(5\ \text{kA})^2 = 112$ H. Because all eight, 2-m coils are in series electrically, the current is always the same in all modules we ignored the various mutual inductances.

7. Turn-to-turn insulation

   Thickness = (1/87)[1812 mm - (88 x 18 mm)] = 2.62 mm = 0.103 in

8. Layer-to-layer insulation

   Thickness = (1/6)[212 mm - (7 x 26 mm)] = 5.0 mm = 0.197 in

9. Length of conductor in module

   Length (2m) ~ [π (9.5 m/turn)](616 turns) =18.4 km

10. Total length of conductor required

    Assuming eight, 2-m modules, i.e. no spares, and no cutting loss,

    Length (16m) = 8 x 18.4 km = 147 km = 92 miles

CONDUCTOR

11. Overall conductor dimensions

Keep the same conductor as before, but fewer turns per layer and correspondingly thicker turn-to-turn insulation.

12. Peak field at the conductor

Bob Wands has found that the highest fields occur at the coil I.D. at the longitudinal mid-point of the modules, where the field has only an axial component. The total field at the outside-longitudinal--inside-radial corner is about 1.3 T.

13. Short sample conductor specification

The superconductor current density of 3×10^9 A/m^2 came from Al McInturff in 1988. An Outokumpu brochure gives 4×10^9 A/m^2 at 3 T and 4.2 K. The choice of 10 kA at 2 T is sort of arbitrary, based partly on the requirement for the CDF conductor (10.4 kA @ 1.5 T).

14. Cu:SC area ratio

$$A_{SC} = 10 \times 10^3 \text{ A}/3 \times 10^9 \text{ A/m}^2 = 3.33 \times 10^{-6} \text{ m}^2$$

$$A_T = 0.018 \times 0.126 \text{ m}^2 = 4.68 \times 10^{-4} \text{ m}^2$$

$$A_{Cu} = 4.65 \times 10^{-4} \text{ m}^2$$

$$A_{Cu}/A_{SC} = 4.65 \times 10^{-4}/3.33 \times 10^{-6} = 141$$

15. Conductor-copper current density

$= 5000 \text{ A}/4.68 \times 10^{-4} \text{ m}^2 = 1.07 \times 10^7 \text{ A/m}^2 = 1070 \text{ A/cm}^2 \sim 11 \text{ A/mm}^2$. It is interesting to note that AWG 16 (ϕ = 0.0508" = 1.29 mm) copper wire is rated for 10 A in household use, a current density of 7.6 A/mm^2.

16. Copper RRR

Although the RRR of typical superconductors can reach 250 in the drawing process, the spooling and winding strain will reduce that. The magnetoresistance effect will increase the resistivity, and decrease the RRR, by about a factor of two at 2 T.

17. Copper resistivity

We used the value at 273 K from the Superconducting Machinery Handbook at an RRR = 100, 1.55×10^{-10} Ω-m. An ORNL reference gives $\rho = 1.48 \times 10^{-10}$ at 2 T for annealed OFHC copper.

18. Full surface heat flux

Heat flux = $I^2\rho/2(ab)(a + b)$ [Design Note #18]. We used I=5000 A,
$\rho = 1.55 \times 10^{-10}$ Ω-m, a = 1.8 cm, b = 2.6 cm. The heat flux is so low that the wetted fraction does not matter very much.

19. Critical current margin

We adopted the General Dynamics definition of this, found in their MFTF report GDC-LLNL-84-001, p. 11-14:

$$\text{Crit.C.M.} = [(I_c - I_{op})/I_{op}]_{Bop}.$$

We constructed the B-I short sample curve (Fig. 1) on either side of the 10 kA/2 T point using the Outokumpu data sheet (Fig. 2).

$$\text{Crit.C.M.} = [(10.5 - 5\text{ kA})/5\text{ kA}]_{1.8T} = 1.1 = 110\%$$

20. Critical field margin

The GDC definition:

$$\text{Crit.F.M.} = [(B_c - B_{op})/B_{op}]_{Iop} = [(5.3 - 1.8\text{ T})/1.8\text{ T}]_{5kA} = 1.94$$

21. Cryostable current margin

Again the GDC definition: $\text{Cryo.C.M.} = [(I_s - I_{op})/I_{op}]_{Bop}$.

GDC defines the cryostable current I_s (page 9-290 as the current which gives a surface heat flux equal to the minimum film boiling recovery flux. Van Sciver, "Helium Cryogenics", p. 219, gives the MFBF = 0.3 W/cm^2. For the 18 x 26 mm conductor at 5 kA, the heat flux is ~ 0.01 W/cm^2. Then

$$I_s^2 = (0.3/0.01)\ I_{op}^2 = 30\ I_{op}^2 \text{ and } I_s = 5.48\ I_{op} = 27.4\text{ kA}.$$

$$\text{Cryo.C.M.} = [(27.4 - 5\text{ kA})/5\text{ kA}]_{1.8T} = 4.48$$

These three margins were 0.10 (10%) for the MFTF solenoids.

22. Fraction of short sample on load line

The operating point (5 kA, 1.8 T) is 0.611 (61.1%) of the way along the B_{max} load line, which intercepts the short sample curve at (8.3 kA, 2.9 T).

23. Temperature margin

On the B_{max} load line the point (8.3 kA, 2.9 T) is at 4.2 K, the point (0,0) is at 10 K. We assumed a linear decrease of (I,B) along the load line. The operating point is 0.389 (38.9%) of the way from 4.2 to 10 K. The maximum temperature at which the coil will remain superconducting at the operating point is 4.2 + 0.389(10 - 4.2) K = 4.2 + 2.26 K = 6.46 K. The temperature margin is 2.26 K.

QUENCHING

24. Fast discharge resistor

The value of the FDR was chosen to give an initial terminal voltage of 500 V during a fast, non quenching discharge from 5 kA. The coil is center tapped to ground (Design Note #31) so the maximum terminal voltage to ground is 250 V.

25. Nominal fast discharge time constant

The value is simply the coil inductance divided by the FDR, τ_{FD} = 112 H/0.1 Ω = 1120 s. This will be the time constant for a fast, but non-quenching discharge. The time constant for a quenching discharge will doubtless be less than this over most of the discharge because eddy current heating in the coil will cause the resistance to grow quickly enough that the coil resistance, $R_Q(t)$, enters into the equation for the time constant, $\tau = L/[R_D + R_Q(t)]$.

26. $U(\theta_m) = {}_0\int^{\infty} J^2(t)\ dt$

Reference: Wilson, "Superconducting Magnets", p. 201, 219

The value calculated from $U(\theta_m) = (0.5)J^2\tau_{FD} = (0.5)(1.07 \times 10^7)^2(1120) = 6.41 \times 10^{16}\ A^2\text{-s-m}^{-4}$ is a maximum since the quenching time constant will be less than 1120 s.

27. ${}_0\int^{\infty} I^2(t)\ dt$ -- MIITS

This is simply $A_{Cu}U(\theta_m)$

28. Maximum adiabatic hot spot temperature, θ_m

From Wilson, "Superconducting Magnets", Fig. 9.1, p. 202:

$U(\theta_m)$	ρ_0 (Ω-m)	θ_m (K)
6.5×10^{16}	1×10^{-10}	85
"	5×10^{-10}	120
"	1.55×10^{-10}	90

The value at 1.55×10^{-10} Ω-m is a linear interpolation between the other two points.

29. Initial/maximum eddy current heating in conductor during fast discharge
Reference: Design Note #25

P(t){conductor, 2-m module} = $(N/R_C)(A_{eff}\ dB/dt)^2$

With N = 616, R_C = 1.55 (6.4 μΩ) = 9.92 μΩ, A_{eff} = 0.78 m^2

P(t){conductor, 2-m module} = $37.8 \times 10^6\ (dB/dt)^2$

P_m{cond, 2-m} = maximum power in the conductor of a 2-m module
= P_0{cond, 2-m module} = $(N\ A_{eff}^2/R_C)(dB/dt)_0^2$

= $37.8 \times 10^6\ (B_0/\tau)^2$ = 87.1 W and

P_m{conductor, eight 2-m modules} = 697 W

E{cond, 8 x 2-m} = energy deposited in conductor during fast discharge
= $(\tau/2)P_m$ = 390 kJ

30. Initial/maximum eddy current heating in helium vessel during fast discharge
Reference: Design Notes # 20 and 25
During any discharge
$$P(t)\{\text{He vessel}\} = (M\ dI/dt)^2/R\{\text{He vessel}\}$$

During a fast, non-quenching discharge, the maximum power occurs at t_0
$$P_0\{\text{He vessel}\} = (MI_0/\tau_{FD})^2/R\{\text{He vessel}\}$$

For an 8-m He vessel $M = 0.028$ H, $I_0 = 5000$ A, $\tau_{FD} = 1120$ s, R{8-m He vessel} = 21.1 $\mu\Omega$

$$P_m\{\text{8-m He vessel}\} = 740.5\ \text{W},\quad P_m\{2 \times \text{8-m He vessel}\} = 1481\ \text{W}$$

$$E\{2,\ \text{8-m He vessels}\} = (\tau_{FD}/2)P_m = 829\ \text{kJ}$$

31. Total energy deposited into coils and He vessels during a fast discharge
$$E\{\text{total}\} = 390 + 829\ \text{kJ} = 1219\ \text{kJ}$$

32. Liquid helium boiled during fast discharge

A simple-minded calculation is to apply the energy deposited into the cold mass to boiling LHe at one atmosphere, dividing the energy by the heat of vaporization, 1219 kJ/ 2.56 kJ/liquid liter = 475 liquid liters. If the gas from this quantity of boiloff liquid is removed from the magnet system to the refrigerator without raising the pressure/temperature, then this method and value is correct. If this is not the case, then part of the energy goes into raising the internal energy (temperature) at constant volume. The rate at which liquid is boiled is actually an exponential function of time. Furthermore, a fast discharge will almost surely initiate a quench, in which case the rate at which heat is added to the helium and cold mass will obviously be greater than for a non-quenching fast discharge. We have not attempted to do the comprehensive calculation of the pressure in the helium vessel as a function of time after initiation of a fast discharge or a quench or the rate of venting of helium after the reliefs open.

33. Quenching after initiation of a fast discharge

To investigate whether a quench will be initiated by the eddy current heating in the conductor, We considered the heat flux from the surface of the conductor in a 2-m module, at the time of maximum eddy current heating,
$$Q/A = 87.1\ \text{W}/2(1.8 + 2.6\ \text{cm})(18.4 \times 10^5\ \text{cm}) = 5\ \mu\text{W/cm}^2,$$
which is in the nucleate boiling regime and a normal spot will collapse rather than propogate. However, the heat flux to a 2-m helium vessel (185 W) will either boil away or blow out the liquid helium surrounding the coil and it will probably quench--I'm guessing that the gas remaining within the coil won't sustain even this low heat flux.

CHARGING AND SLOW DISCHARGE

34. Power supply voltage and current

A charging voltage of 100 V (50 V to ground) gives a linear charge time of about 1.5 hours. In order to provide a linear charge to the operating current of 5 kA, the power supply will be capable of 6 kA which it will deliver just as the coil reaches the operating current (5 kA through the coil and 1 kA through the fast discharge resistor). The supply will be rated at 600 kW. The steady state power would probably be a few volts at 5 kA.

35. Charge rate at constant voltage

$V = L\ (dI/dt)$; $dI/dt = V/L = 100\ V/112\ H = 0.893\ A/s$

36. Charge time with constant voltage

Charge time $= 5000\ A/0.893\ A/s = 5600\ s = 93.3$ min

37. Slow discharge resistor

A slow discharge consists of two time segments. During the initial, exponential portion the terminal voltage drops exponentially from an initial value to 75 V, the maximum reverse voltage possible from the 100-V power supply (reference: John Stoffel). The coil current is also decaying exponentially from 5000 A during this time. The SDR was chosen so the intial discharge voltage would be the same as the charging voltage, so SDR $= 100\ V/5000\ A = 0.02\ \Omega$. During the exponential portion of the slow discharge the coil current decays from 5000 to 3750 A ($75\%I_0$).

The second portion of the slow discharge is linear at a constant voltage of 75 V. At some low current the reverse power supply voltage will droop, but we have ignored this and assumed a linear discharge from 3750 to 0 A.

38. Slow discharge time constant

$\tau_{SD} = L/SDR = 112\ H/\ 0.02\ \Omega = 5600\ s.$

39. Exponential slow discharge time, 100 to 75 V, 5000 to 3750 A

In general $I(t) = I_0 \exp(-t/\tau_{SD})$. At $t = t_1$, $I(t)/I_0 = 0.75$, so

$-(t_1/5600) = \ln(0.75)$ and $t_1 = 1611$ s.

40. Linear slow discharge time, 3750 to 0 A

From t_1, $I_1 = 3750$ A to t_2, $I_2 = 0$

$dI(t)/dt = V(t)/L = 75/112 = 0.67\ A/s$ and $(t_2 - t_1) = 3750/0.67 = 5600$ s

41. Total slow discharge time, from 5 kA

$t_2 = t_1 + (t_2 - t_1) = 1611 + 5600\ s = 7211\ s = 2\ h$

42. Eddy current heating--general

Power

$$P(t)\{8\text{-m He vessel}\} = [M\ dI(t)/dt]^2/R\{8\text{-m He vessel}\}$$
$$= [M\ V(t)/L]^2/R\{8\text{-m He vessel}\} = [(0.028/112)^2/21.1 \times 10^{-6}]\ V^2(t)$$
$$= (0.00296\ W/V^2)\ V^2(t)$$

$$P(t)\{2,\ 8\text{-m He vessels}\} = (0.00592)\ V^2(t)$$

$$P(t)\{2\text{-m coil}\} = 37.8 \times 10^6\ (dB/dt)^2$$
$$= 37.8 \times 10^6\ [(1.7\ T/5000\ A)\ dI/dt]^2$$
$$= (37.8 \times 10^6)(0.1156 \times 10^{-6})[V(t)/L]^2$$
$$= [(37.8)(0.1156)/(112)^2]\ V^2(t)$$

$$= (0.000348\ W/V^2)\ V^2(t)$$

$$P(t)\{8,\ 2\text{-m coils}\} = (0.00279)\ V^2(t)$$

$$P(t)\{total\} = (0.00871)\ V^2(t)$$

Energy

$$E = \int P(t)\ dt$$

43. Eddy current heating during constant 100-V charge

$$P\{2,\ 8\text{-m He vessels}\} = 59.2\ W$$
$$P\{8,\ 2\text{-m coils}\} = 27.9\ W$$
$$P\{total\} = 87.1\ W$$

$$E\{total\} = (87.1\ W)(5000\ A/0.893\ A/s) = 488\ kJ = 190\ L\ LHe$$

44. Eddy current heating during slow discharge

Exponential portion, $t_0 = 0$ to $t_1 = 1611$ s; $V_0 = 100$ to $V_1 = 75$ V

$$P_0\{2,\ 8\text{-m He vessels}\} = 59.2\ W$$
$$P_0\{8,\ 2\text{-m coils}\} = 27.9\ W$$

$$P_1\{2,\ 8\text{-m He vessels}\} = (0.00592)(75)^2 = 33.3\ W$$
$$P_1\{8,\ 2\text{-m coils}\} = 15.7\ W$$

$$E_{0,1}\{total\} = {}_0\int^1 P(t)\ dt = (0.00871)\ {}_0\int^1 V^2(t)\ dt$$
$$= (0.00871)\ {}_0\int^1 V_0^{\ 2} \exp(-2\ t_1/\tau)\ dt$$
$$= (0.00871)V_0^{\ 2}\ (-\tau/2)\ [\exp(-2t_1/\tau) - \exp(-2t_0/\tau)]$$
$$= (0.00871)(10000)(5600/2)[1 - \exp(-2 \times 1611/5600)$$
$$= 244\ kJ\ [1 - \exp(-0.572)]$$
$$= 244\ kJ\ (1 - 0.563) = 107\ kJ$$

Linear portion

$$P_{1,2}\ \{total\} = 33.3 + 15.7\ W = 49\ W$$

$$E_{1,2}\{total\} = (49\ W)(5600\ s) = 274\ kJ$$

Entire discharge

$$P_m\{total\} = P_0\{total\} = 59.2 + 27.9\ W = 87.1\ W$$

$$E_{0,2}\{total\} = 107 + 274\ kJ = 381\ kJ = 149\ L\ LHe$$

45. Summary of eddy current heating

	Charge	Fast Discharge	Slow Discharge	
V_{max}	100. (const)	500. (exp)	100. (exp)	75. (const)
P_m\{2, 8-m vessels\}--W	59.2 (const)	1481. (exp)	59.2 (exp)	33.3 (const)
P_m\{8, 2-m coils\}--W	27.9 (const)	697. (exp)	27.9 (exp)	15.7 (const)
P_m\{total\}--W	87.1 (const)	2178. (exp)	87.1 (exp)	49.0 (const)
Energy--kJ	488.	1219.	107.	274.
			381.	
LHe boiled--L	190.	475.	149.	

(const) and (exp) indicate constant or exponentially decaying values

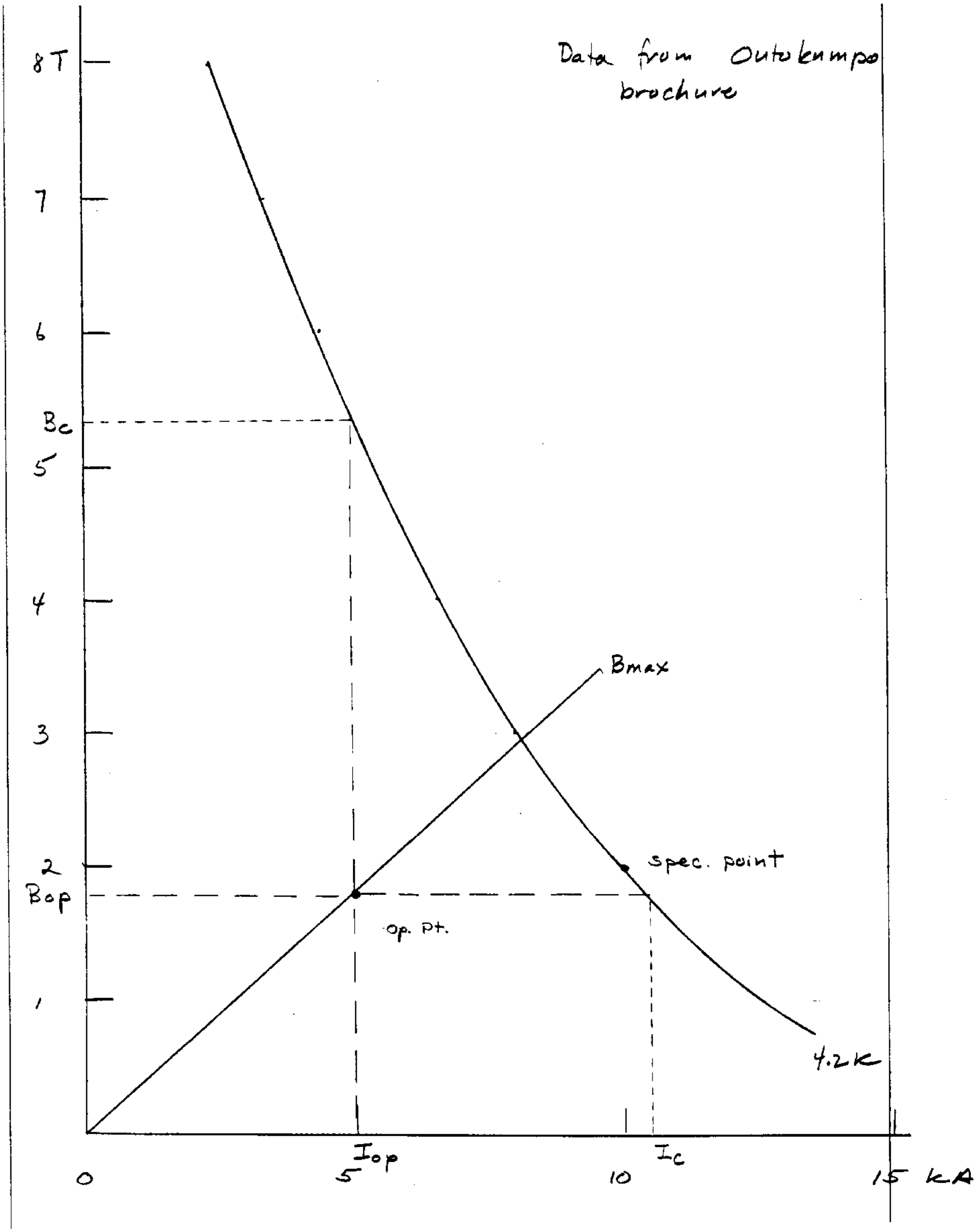
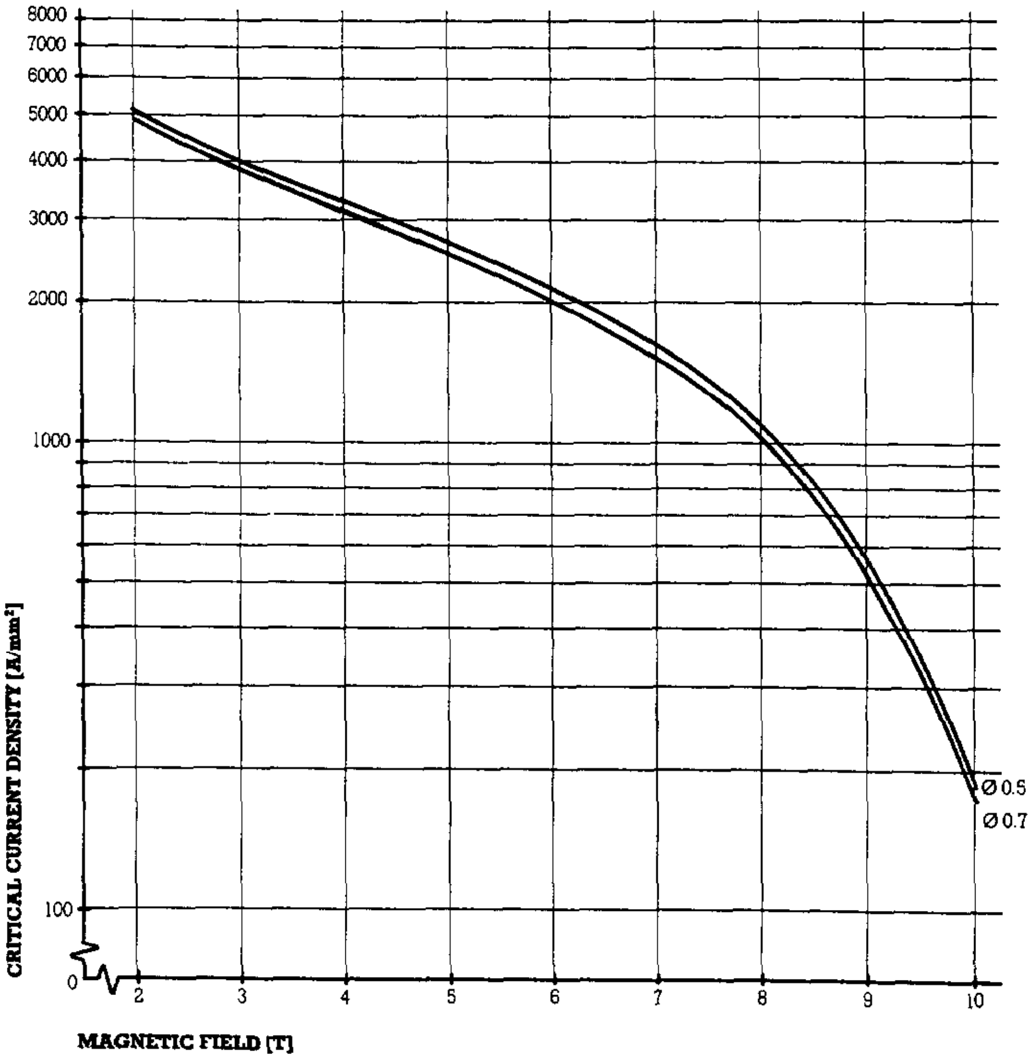


Fig. 1. Short-sample curve and load line



Guaranteed critical current densities v.s. magnetic field at 4.2 K using a criterion of 10^{-14} Ω m for multifilament Cu/NbTi wires. Upper curve for Ø 0.5 mm and lower curve for Ø 0.7 mm SCOK 20 - SCOK 60 wire types.

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Fig. 2. Superconductor current density (from Outokumpu)

Appendix C: Magnetic Field and Force Calculations

ABSTRACT

The preliminary design of a large detector for the high energy physics program of the Superconducting Super Collider (SSC) is centered about a large superconducting solenoid magnet producing a field of 1.7 T over a volume 8 meters in diameter by 16 meters long. Reliability is emphasized due to the difficulty of performing any maintenance or replacement after installation. An important factor in determining reliability is the accuracy with which the solenoid field and electromagnetic forces can be calculated. The ANSYS general purpose finite element program, with 2-d and 3-d magnetostatic capabilites, was used to calculate magnetic field, Lorentz forces, and stored energy for the proposed solenoid geometry. Axial forces resulting from failure of individual coils were found to be much greater than those expected from initial axial offset of the solenoid from the magnetic center of the iron. Radial decentering forces were found to be negligible in comparison with the overall solenoid weight. Comparison of the 2-d and 3-d finite element results for field and forces in normal operation showed good agreement.

INTRODUCTION

The ANSYS general purpose finite element program has been used previously in the analysis of superconducting detector and accelerator magnets[1,2]. This paper will examine it's use in the 2-d and 3-d analysis of a proposed SSC large detector solenoid, with an emphasis on the effects of mesh refinement and iron characterization on the resulting forces for various normal and upset conditions.

MAGNETOSTATIC ANALYSIS WITH ANSYS

Magnetostatics belongs to a large class of engineering problems which respond to solution of the Laplace and Poisson equations for potential distribution. Heat conduction, seepage through porous media, and torsion of prismatic shafts are examples of other common problems of the same class. The finite element method is well established as a stable and accurate method of solving these problems.

Two-dimensional magnetostatics is solved by the vector potential approach in ANSYS[3], and is exactly analogous to 2-d heat conduction. The 3-d problem, however, presents special difficulties in a finite element solution, one of which is the three nodal degrees of freedom required by a vector potential formulation. To reduce the degrees of freedom and preserve the heat conduction analogy, ANSYS uses a reduced scalar potential formulation in which the field intensity H is calculated in two parts. The first part is due to source currents and is found from integration of the Biot-Savart law. The second part is the induced magnetization and is found from a finite element formulation[3,4]. This can lead to numerical cancellation problems when the induced magnetization and current source contributions are nearly equal, as occurs in highly permeable regions.

Lorentz forces on current sources and the Maxwell stress tensor forces on ferromagnetic regions are calculated from the field solution. In the 2-d case, ANSYS calculates and stores the Lorentz forces during the solution phase; these can then be listed directly during post-processing. The Maxwell stress tensor forces can be calculated by the user in the post-processing phase by defining a path through the air around a ferromagnetic region. ANSYS then performs the necessary integration to calculate the forces.

The calculation of forces in 3-d varies depending on the way in which the current sources are modeled. Standard source shapes such as bars, arcs, and coils can be input in terms of a few geometric parameters, which are then used for the Biot-Savart integration. The sources do not exist as finite elements, and the program does not calculate and store Lorentz forces for them. However, the user can perform the Lorentz force calculations using the post-processor and the field solution.

Complex 3-d source shapes may be modeled with finite elements which carry a specified current. The program calculates the Lorentz force on each element from the field solution and element current density. Regardless of source definition, forces on ferromagnetic regions can be calculated by a method of virtual work during the solution phase, and retrieved during post-processing.

Although ANSYS has recently added full 3-d vector potential and difference scalar potential elements, these were not available at the time this analysis was done.

THE PROPOSED SSC DETECTOR SOLENOID

An axisymmetric cross section of the proposed SSC detector solenoid is shown in Fig. 1 and consists of eight superconducting, pool-boiling coils, each 1.8 meters in magnetic length and 5 meters in radius. Four coils are assembled into an 8-m assembly, with the two assemblies independently supported in the magnet iron.

The magnet iron is octagonal in cross section, and includes endplugs which can, if necessary, be designed to extend into the bore of the outermost coils.

OBJECTIVES OF THE ANALYSIS

The objective of the analysis was to determine:

1. The correct current density for real iron to produce a central field of 1.7 T,

2. The amount of endplug "re-entry" into the bore of the outermost coils to eliminate axial force for nominal assembly,

3. The decentering forces resulting from initial installation offsets of the solenoid from the magnetic center of the iron.

4. The maximum safe test current for single coil without iron,

5. The maximum stored energy and inductance,

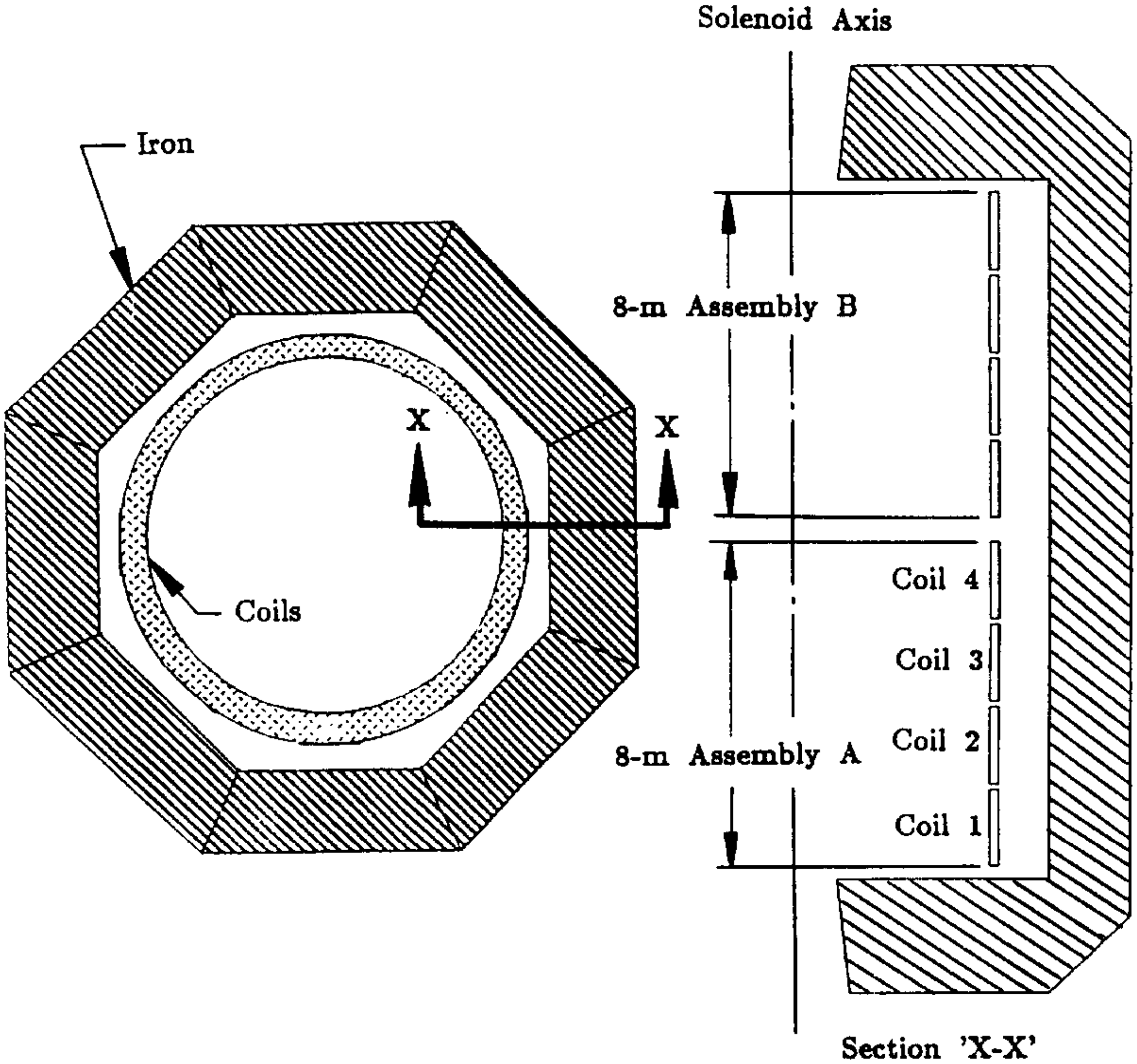


Fig. 1. SSC detector solenoid.

6. The axial forces resulting from the failure of a single coil module and consideration of the possiblity of designing for operation with less than eight coils energized to full current, and

7. Verification.

TWO-DIMENSIONAL FINITE ELEMENT MODELS

All of the analysis objectives except the radial decentering force may be met with a 2-d axisymmetric finite element anslysis. A typical mesh is shown in Fig. 2. This mesh, using elements which are a maximum of 0.5 meters on a side, results in approximately 200 cp seconds/iteration on a VAX3200 workstation. Up to 20 iterations were required by some runs to achieve convergence with real iron. The full model was necessary for coil failure and axial decentering analyses; during normal operation only one half of the solenoid need be modeled.

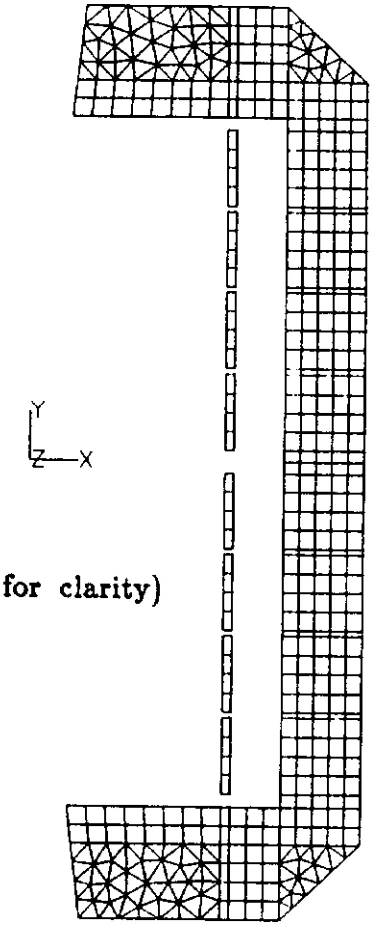


Fig. 2. 2-d axisymmetric finite element model.

Operating current for 1.7 T central field. The current required for a central field of 1.7 tesla was found for meshes with element sizes varying from 1 meter to 0.125 meters. Runs with infinitely permeable iron showed that the necessary current density was $7.3(10^6)$ A/m^2. For the proposed 616 turns of conductor in each coil, the superconductor operating current was 4560 amps. The central field varied by less than 0.1% over the range of element sizes considered. Later runs used a real B-H curve for typical 1020 magnet iron with both 0.5 and 0.25 meter element sizes, and the central field decreased by about 0.5% from the infinitely permeable iron results.

Re-entrant iron to minimize axial force. Results of runs with infinite iron permeability showed that the endplug iron should end approximately 0.3 meters outside of the bore of the outermost coil in order to minimize the axial force for a "perfectly" installed 8-m assembly. Refined models with real iron verified this result.

Axial decentering forces. These forces can result from installing the 8-m assemblies offset axially with respect to the magnetic center of the iron yoke. Five load cases were considered, using real iron and an element size of 0.5 meters. The results are summarized in Table 1. The maximum force was found for the case of a 25 mm displacement of each of the 8-m assemblies toward the center of the solenoid, and was 12400 kN.

Table 1. Axial Decentering Forces

Load Case and Axial Offset	Force on 8-m assembly
1. 8-m assembly A: 25 mm	11600 kN
8-m assembly B: nominal	10200 kN
2. 8-m assembly A: 25 mm	12400 kN
8-m assembly B: 25 mm	12400 kN
3. 8-m assembly A: 25 mm	10700 kN
8-m assembly B: -25 mm	4000 kN
4. 8-m assembly A: -25 mm	2700 kN
8-m assembly B: -25 mm	2700 kN
5. 8-m assembly A: -25 mm	11600 kN
8-m assembly B: nominal	8900 kN

Note: Positive offsets and forces are toward solenoid midplane

Maximum test current for coil. The coils will be tested without iron, and so will be subjected to large compressive forces. The maximum test current was established by finding the worst case operational compressive force, and calculating from a finite element model of a coil in air the current which will produce that force. In normal operation, the maximum force occurs in the coils at the ends of the solenoid, and is 13300 kN. A finite element model of a single coil shows that a current density of $1(10^6)$ A/m^2 gives a maximum coil force of 300 kN. Scaling this force gives a maximum test current density of $6.5(10^6)$ A/m^2, or 4060 amps.

Maximum stored energy and inductance. The stored energy from the two-dimensional models was calculated in the post-processing phase by performing a numerical integration over the volume of the conductor region of the product of the magnetic potential and the current density. The inductance can then be calculated from the stored energy and the total current. The stored energy for normal operation was found to be 1400 MJ, while the inductance was 112 H.

Axial forces due to coil failure. The coils may be individually energized, and the magnetic field and axial forces resulting from running the magnet with a failed coil were calculated. Figure 3 shows the variation of the field with coil failure. Resulting axial forces are shown in Table 2. The maximum axial force of 54200 kN occurs on 8-m assembly A when coil 1 fails.

THREE-DIMENSIONAL FINITE ELEMENT MODELS

The calculation of the radial decentering force on an 8-m module assembly requires a 3-d finite element model of one-half of an 8-m assembly (Fig. 4). There are approximately 9000 nodes and elements, and one iteration of the model requires 6100 cp seconds on a VAX3200 workstation.

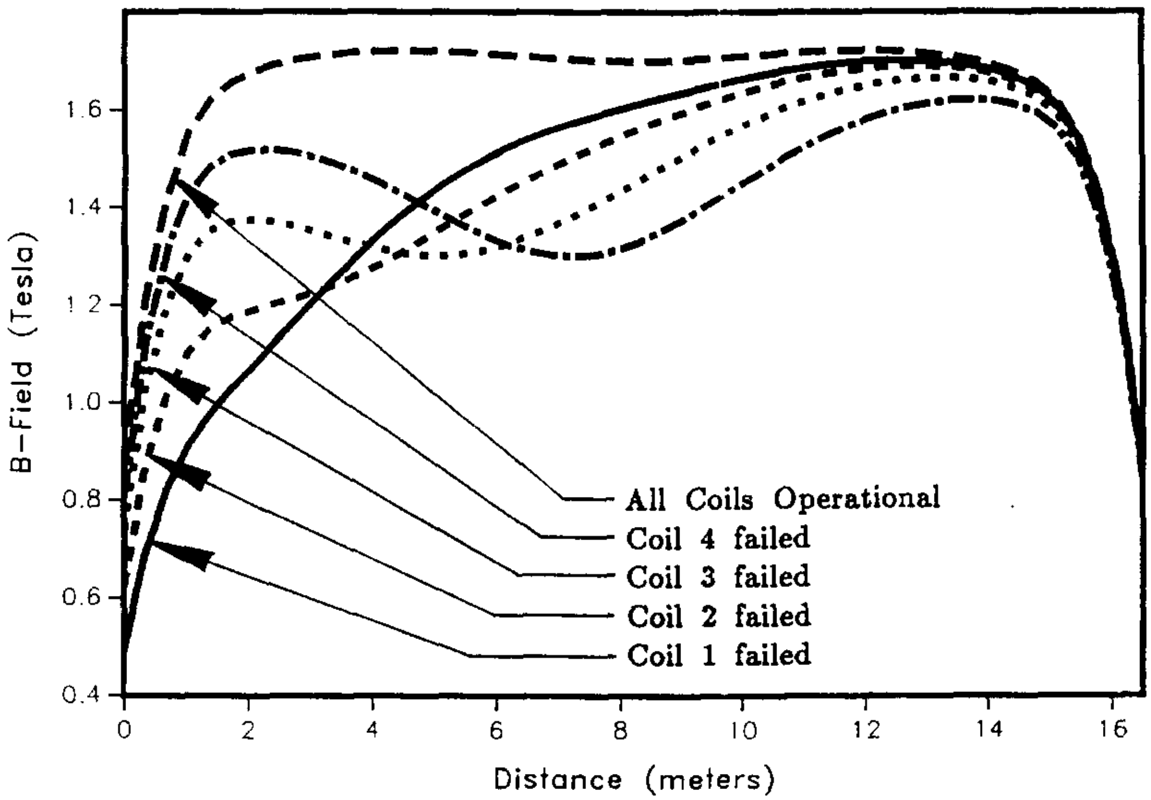


Fig. 3. Field on solenoid axis for coil failure scenarios.

Table 2. Maximum Axial Force on 8-m Assembly
Due to Individual Coil Failure

Failed Module (see Fig. 1)	Model Characteristics		
	Inf. mu, 0.5 mm element	Inf. mu, 0.2 mm element	Real iron, 0.50 mm element
Coil 1	54200 kN 8-m assembly A	54200 kN 8-m assembly A	53800 kN 8-m assembly A
Coil 2	23400 kN 8-m assembly A	23400 kN 8-m assembly A	23350 kN 8-m assembly A
Coil 3	-15300 kN 8-m assembly B	-15400 kN 8-m assembly B	-15000 kN 8-m assembly B
Coil 4	-37000 kN 8-m assembly B	-36900 kN 8-m assembly B	-36700 kN 8-m assembly B

Note: Positive force is toward solenoid midplane

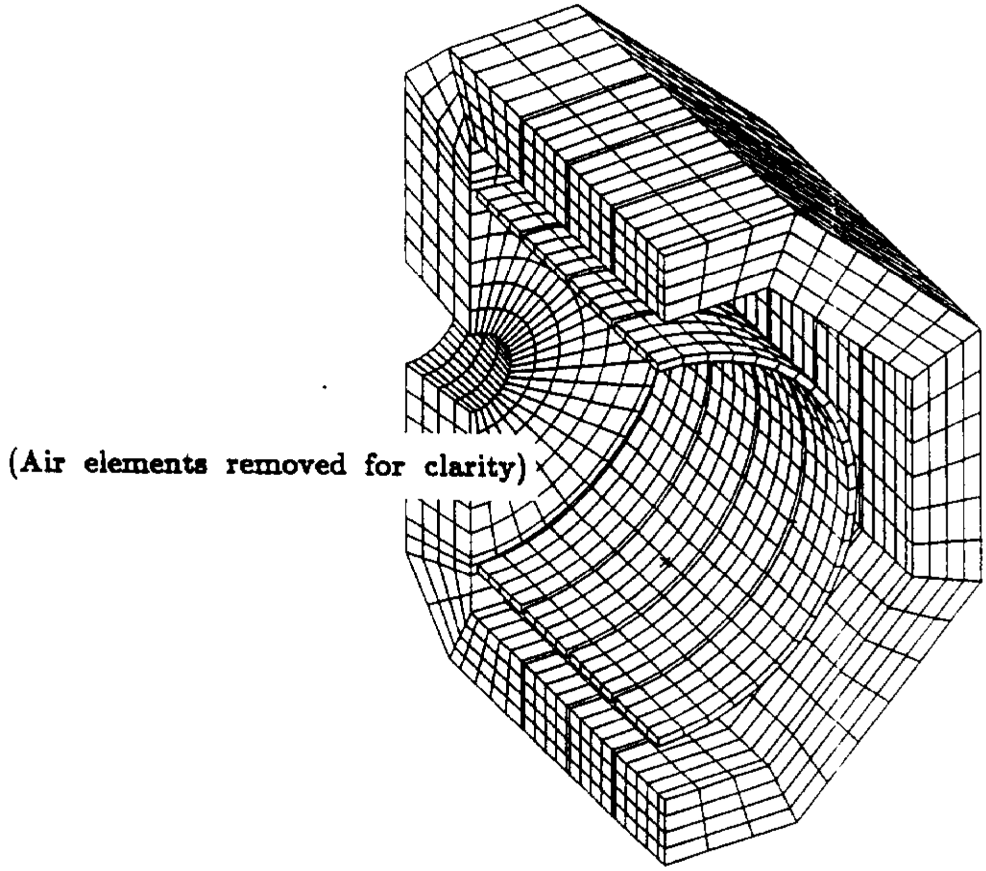


Fig. 4. 3-d finite element model.

Radial Decentering Force. This force was found by displacing the coil centroids by 25 mm along the x-axis of the model. The coil elements were also displaced by 25 mm so that they were coincident with coil definitions. The virtual work option was used for force calculation. The results of the model showed that the radial decentering force resulting from a 25 mm offset from magnetic center was 200 kN.

VERIFICATION

Some analytical calculations can be made with which FEA results can be compared. For example, the original coil dimensions and currents were established by approximate hand calculations, and the FEA provided reasonable refinements of these for the present design. Stored energy, calculated by the assumption of uniform 1.7 T central field, is 1600 MJ, comparing with 1400 MJ from the FEA.

Another good indication of modeling accuracy is comparison of 2-d and 3-d FEA results for identical loadings.

Comparison of 2-d and 3-d FEA results. A 3-d model with 1/16th azimuthal symmetry was given the same current density as the 2-d model with infinitely permeable iron and an element size of 0.5 m. Figure 5 shows the absolute difference of the axial field as calculated by the two models. Agreement was within 0.03 T at all points, and much better near the center of the solenoid.

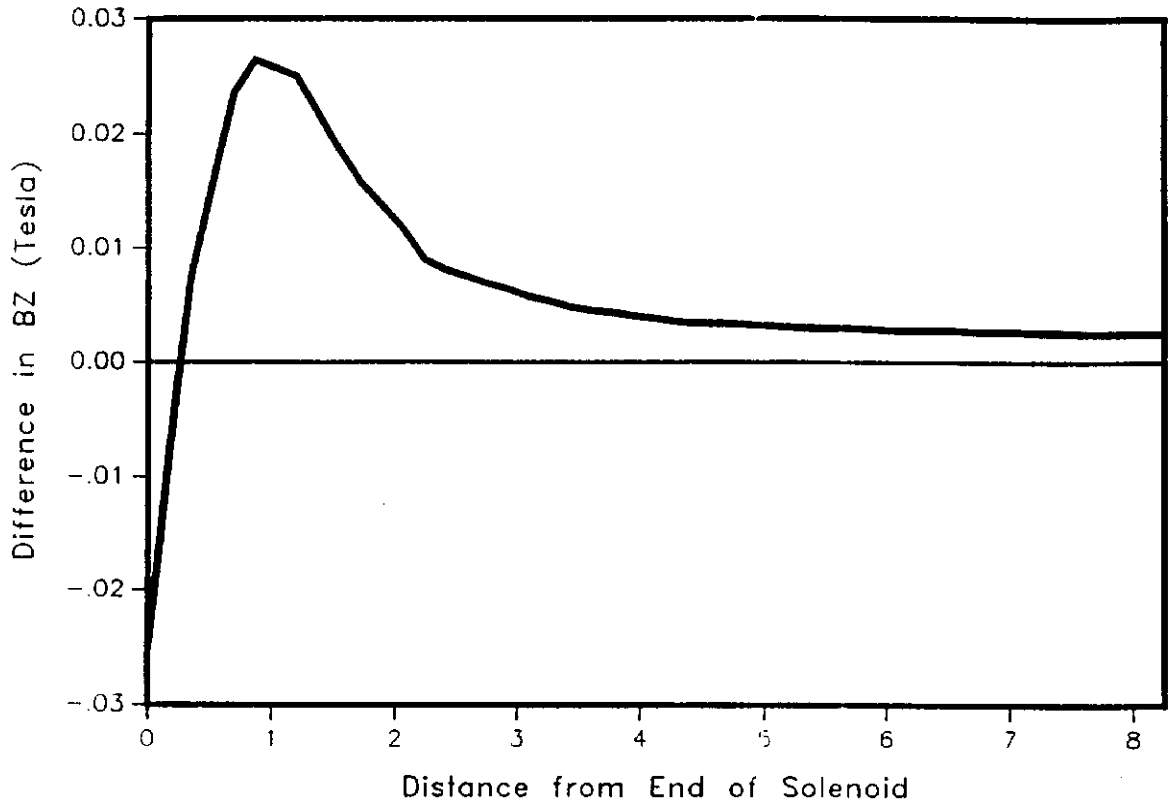


Fig. 5. Difference in axial field for 2-d and 3-d models.

The forces on the coils were extracted from the 3-d model through the post-processor by taking the cross product of the current density and the radial component of the B-field. These forces were compared with those from the 2-d model and found to agree to within 7% for all modules.

CONCLUSION

The 2-d and 3-d magnetostatic analysis of the SSC solenoid was a straightforward application of the ANSYS program. The largest axial force of 54200 kN on an 8-m assembly was found for a coil module failure scenario. Radial decentering forces were negligible. These results canpes be used to establish the design forces for the 8-m assembly support systems.

REFERENCES

1. M. Johnson, R. Wands, and E. Wolin, Design of Electromagnetic Devices Using Commercial Finite Element Programs, Rev. Sci Instrum., Vol. 58, No. 12 (1987)
2. R. Wands and M. Chapman, Finite Element Analysis of Dipole Magnets for the Superconducting Super Collider, in "ANSYS 1989 Conference Proceedings", Vol. II, Swanson Analysis Systems, Inc., Houston, Penn., (1989), p. 7.42
3. D. Ostergaard, "Magnetics for Static Fields," ANSYS Revision 4.3 Tutorials, Vol. II, Swanson Analysis Systems, Inc., Houston, Penn., (1987)
4. O. C. Zienkiewicz, J. Lyness, and D.J.R. Owen, Three-Dimensional Magnetic Field Determination using a Scalar Potential, IEEE Transactions on Magnetics, Vol. Mag. 13, No. 5 (1977)

Appendix D: Ground Transportation of Solenoid Modules

BELDING CORPORATION

130 WEST GRAND LAKE BOULEVARD
P.O. BOX No. 227
WEST CHICAGO, IL 60185-0227

Suburban: (312) 231-5200
Chicago: (312) 287-0104
FAX: (312) 231-0318

December 9, 1988

Mr. Bob Shovan
Fermi National Accelerator Laboratory
M S 318
P. O. Box 500
Batavia, IL 60510

Reference: Moving eight (8) coils
33 ft. in diameter - 7 ft. high
Weighing 100 tons each
From the water at Galveston, Texas
to Waxahachie, Texas

Dear Mr. Shovan:

Our people believe that the State of Texas would cooperate in every way possible to allow this move to be done. Their suggestion is as follows:

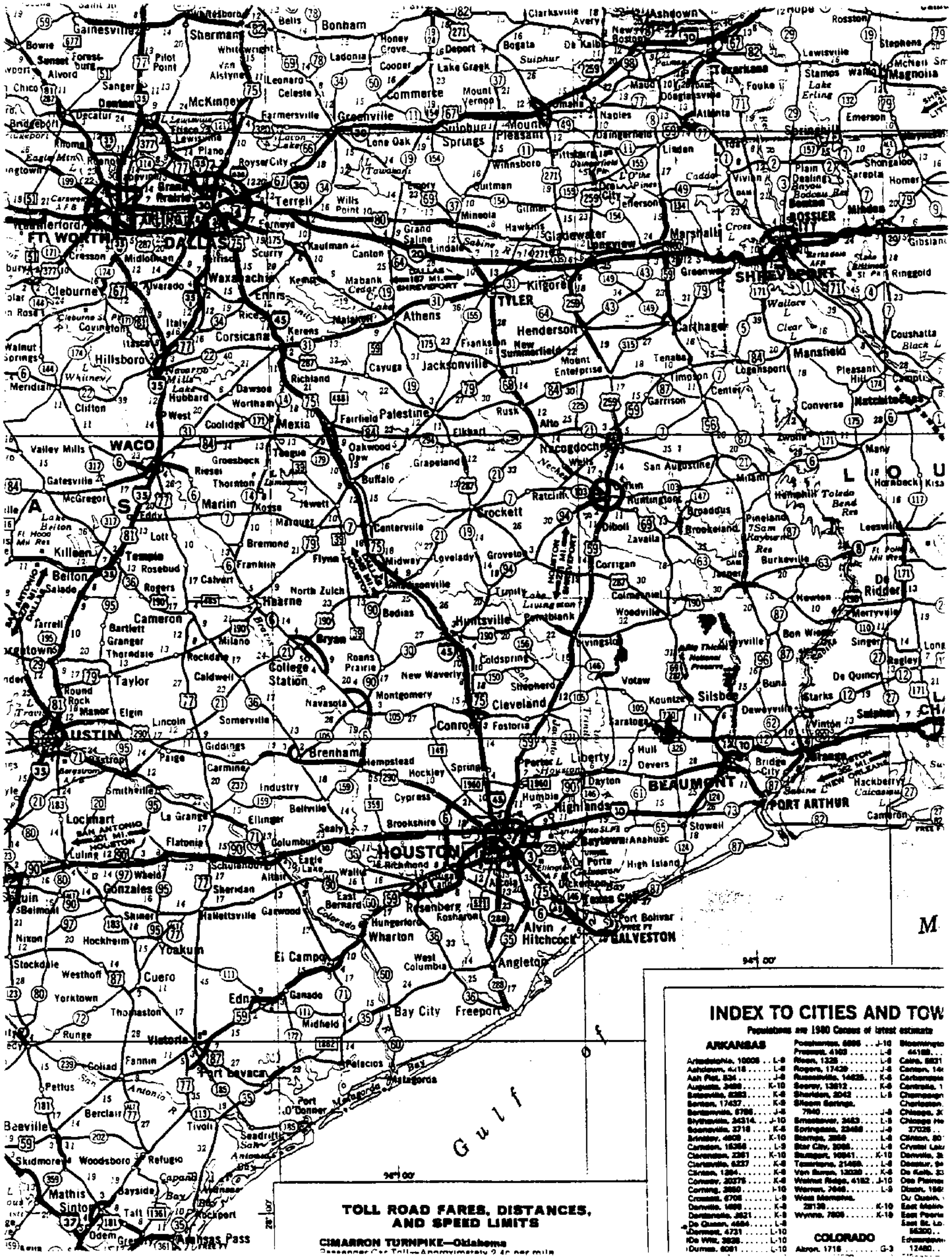
Rather than Galveston, go up the Brasos River at Freeport to Columbia. This stretch has been navigable for barging nuclear products and heavy reactors in the past. We would offload in Columbia, and move up Highway 36 to Sealy.

Then: move West on interstate #10 to Brookshire, then North on Route 359 to Sauney Stand; North on Route 6 to Hearne; then North on Route 14 to Mexia.

From Mexia, take Route 171 Northwest to Brandon; then North on Route 77 to the site at Waxahachie.

Possible cost for this move:

Engineering fee to the State of Texas, which would include examining bridges and possibly moving light and telephone wires for proper clearances: $25,000



Gainesville
Sherman
Bonham
Clarksville
Ashdown
Texarkana
McKinney
Greenville
Sulphur Springs
Mount Pleasant
FT. WORTH
DALLAS
Terrell
Marshall
Longview
SHREVEPORT
Waxahachie
Ennis
Athens
TYLER
Kilgore
Cleburne
Corsicana
Henderson
Carthage
Hillsboro
Jacksonville
Mansfield
Palestine
Mexia
Nacogdoches
WACO
Crockett
Lufkin
Temple
Killeen
Belton
Cameron
Hearne
Huntsville
Bryan
College Station
Taylor
Cleveland
Conroe
AUSTIN
Brenham
Liberty
Beaumont
PORT ARTHUR
HOUSTON
Baytown
Texas City
GALVESTON
Lockhart
Luling
Gonzales
Yoakum
Wharton
El Campo
Angleton
Freeport
Bay City
Cuero
Victoria
Port Lavaca
Beeville
Refugio
Sinton
Aransas Pass
Gulf
INDEX TO CITIES AND TOW
ARKANSAS
COLORADO
TOLL ROAD FARES, DISTANCES, AND SPEED LIMITS
CIMARRON TURNPIKE—Oklahoma

BELDING CORPORATION
130 WEST GRAND LAKE
WEST CHICAGO IL 60185

Page Two

Mr. Bob Shovan
Fermi National Accelerator Lab

December 9, 1988

Actual road improvements, cost of moving poles, bracing bridges or ramping other approaches,etc. $50,000

Cost for moving each piece Approximately $30,000

I hope this information will be helpful to you. Please call us at any time for help.

Sincerely yours,

BELDING CORPORATION

Chip

Chip Belding
Chairman of the Board & CEO

el

Appendix E. Refrigeration System Parameters and Backup Remarks

PARAMETERS

LIQUID NITROGEN CRYOGENIC SYSTEM

Cooling mode	forced flow of subcooled liquid
Average fluid temperature	83 K
Total flow rate	410 g/s
Number of circuits	10 to 12
Expected heat load	5 kW

LIQUID HELIUM CRYOGENIC SYSTEM

Cooling mode	thermosiphon
Number of circuits	14
Module flow rate, gas fraction	25 g/s at 1% gas by weight
Support intercept flow rate, gas fraction	50 g/s at 7% gas by weight
Heat load per 8-m assembly	115 W + 18 L/h (one pair of current leads)
Volume of LHe in coil modules	~10,000 L
Number of storage dewars	2
Capacity of storage dewars	5000 L each
Total heat load of magnet system	230 W + 36 L/h (two pairs of current leads)
Specified refrigerator capacity	1600 - 1800 W

COOLDOWN REFRIGERATOR

Total cold mass	1328 tonnes
Cooldown system	LIN-GHe HTX, with turbo expander
Cooldown time	15 to 20 days

BACKUP REMARKS

LIQUID NITROGEN CRYOGENIC SYSTEM

1. Cooling mode

Reference: Design Note #10. The LIN cooling system is basically a copy of that planned for the SSC ring magnet system, in which the LIN supply is 77-K, 6-ata subcooled liquid and the return 89 K and 4.7 ata. Flow is maintained by liquid circulators (pumps) with a pressure ratio 6/4.7 = 1.28.

2. Average fluid temperature

$= (77 + 89)/2 = 83$ K

3. Total flow rate

Reference: NBS Technical Note 129

$h(77 \text{ K}, 6 \text{ ata}) = 29.000 \text{ J/g} \qquad h(83 \text{ K}, 4.7 \text{ ata}) = 41.228 \text{ J/g}$

Assuming a heat load of 5 kW for the magnet system,
flow rate = 5000 J/s /(41.228 - 29.000) J/g = 409 g/s

4. Number of nitrogen cooling circuits

On each 8-m assembly: (1) inner radiation shield, (2) outer radiation shield, (3 & 4) end radiation shield and radial support intercepts, (5) axial support intercepts. The LHe dewar might have its own circuit (6).

5. Expected heat load

Reference: Design Note 31, paper at IISSC-89.

A value of 50 W is given for the 16-m magnet system in this design note, substantiating calculations are not available.

LIQUID HELIUM CRYOGENIC SYSTEM

6. Cooling mode

We chose a thermosiphon as was used for the MFTF solenoids and the Aleph solenoid at CERN/LEP.

7. Number of circuits

On each 8-m assembly: (1 -4) coil modules, (5) axial support intercepts, (6 & 7) radial support intercepts.

8. Module flow rate/gas fraction

Reference: Design Note #24, paper at ICEC-12; also DN #26 (ASC) and DN #31 (IISSC). These are the only reference documents on this subject. DN #24 gives 23 g/s with <1% by weight, DN #26 and 31 give 25 g/s with <1%

9. Support intercepts flow rate/gas fraction

Design Note #24 gives 50 g/s at <7% gas by weight, DN #26 and 31 give only the 7%.

SSC DETECTOR SOLENOID DESIGN NOTE #10

TITLE: Preliminary LN_2 Shield Cooling

AUTHOR: M.E. Stone

DATE: January 26, 1988

A Preliminary Look At Nitrogen Shield Cooling.

I First consider the size of tube available

use $P = 300$ psi (20 atm)
$t = 0.035$" wall
$S = 18800$ psi (≈0.8 of Fermi mode) - for SS
E = joint efficiency = 1
R = inside radius

$$R = \frac{(SE - 0.6P)t}{P} \quad \text{- cir}$$

$$= \frac{(18800 - 0.6 \times 300)(0.035)}{300}$$

$$= 2.17 \text{ in}$$

$$R = \frac{(2SE + 0.4P)t}{P} \quad \text{- long}$$

$$= [(2)(18800)(0.6) + (0.4)(300)] \times 0.035 / 300$$

$$= 2.65 \text{ in}$$

We will certainly not need a tube with an ID greater than 4.3 in. It is unlikely we would need to use a wall thickness much less than 0.035". Therefore possible pressure requirements should have little effect on the choice of a cooling tube

I What is the heat load to the LN_2 shield

As far as possible scale up from CDF

CDF Heat Load	Axial supports	24 w
	Radial supports	67 w
	Radiation to shells	84 w
	Conduction to shells	176 w

CDF solenoid 3 m ϕ × 5 m long

Super solenoid 10 m ϕ × 16 m long

For a first approximation radiation and conduction to the shells will scale with surface area

The support loads are more complicated. There are forces present here that were not a problem for CDF. The modularzation of the coil may require a change in support scheme. A complete helium vessel will add more cold mass. However more space is available for the supports. For a first estimate double the support heat load and then scale up with surface.

Radiation and Conduction

CDF = 260 w

Surface of the Super Solenoid / CDF = $\frac{10 \times 16}{3 \times 5}$ = 10.6

Use 3000 w for SS (10.6 × 260 = 2756 w)

The length of cooling channel on the CDF shield was ~ 260. Scale this up by surface also Use 3000 ft of cooling channel.

Since there are two completely independent cryostats assume two parallel circuits. Each circuit would have half the cooling channel length (1500 ft) and would have to remove half of the heat load. It may turn out to be desirable to have a seperate circuit for the inner and outer shields but initially will look at them combined

Supports

CDF = 91 W

Doubling and the scaling up by surface results in a heat load of 2000w (91 × 2 × 10.6 = 1929)

The design and placement of the supports is unknown at this time. It is unlikely that the flow path in each cryostat would be greater than 500 ft.

At this point removing the heat load due to the supports will not be considered. At first glance the shield requirements appear more stringent.

III Choose LN_2 cooling similar to the SSC

Under normal operating subcooled liquid is used

A subcooler and a circulating pump are located near coil level.

Only gas is returned to the surface.

Durning cooldown the pumps are not used. Gas is vented after passing through the coil.

See Fig 1

The actual operating pressure will be dependent on the head and the operating pressure of the dewar at the surface

For the moment choose ring conditions

In 6 ata and 78 K H = 31.05 j/g

Out 4.7 ata " 89 K H = 53.64 j/g

Required flow = 1500w ÷ (53.64 − 31.05) j/g = 66.4 g/sec.

Choose a 1" × 0.065" Wall tube

Fig 2 shows ΔP through this tube for single and 2φ flow.

The highest ΔP will be ~ 3 atm. This is not a problem during cool down when a ΔP of ~ 5 atm would be available.

While operating the nitrogen flow should be subcooled by ~2 atm when it exits the magnet so 2ϕ flow is unlikely.

The pressure drop caused by less than 30% gas is small enough not to cause a problem and the heat exchanger could be sized to be able to handle this amount. Beyond 30% gas would probably be vented.

Consider room temperature gas at 6 ata. A flow of 40 g/sec (per tube) would have a pressure drop of ~ 4.5 atm. ΔH from 78 K liquid to 300 K gas is ~ 430 j/g. This would allow an initial cooling rate of 34 kw.

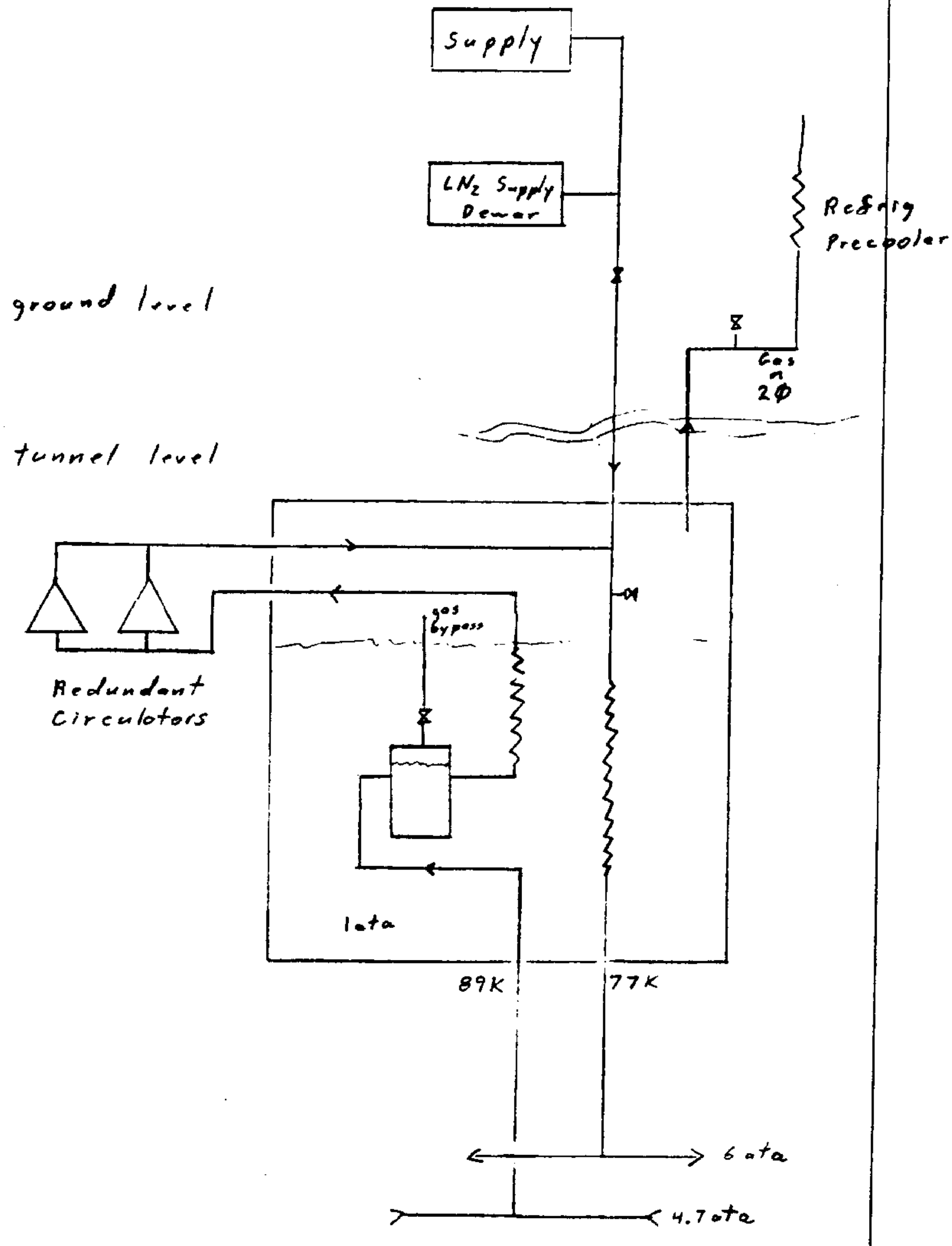

Supply
LN_2 Supply Dewar
Refrig Precooler
ground level
Gas n 2Ø
tunnel level
gas bypass
Redundant Circulators
1ata
89K
77K
6 ata
4.7ata

Fig 1

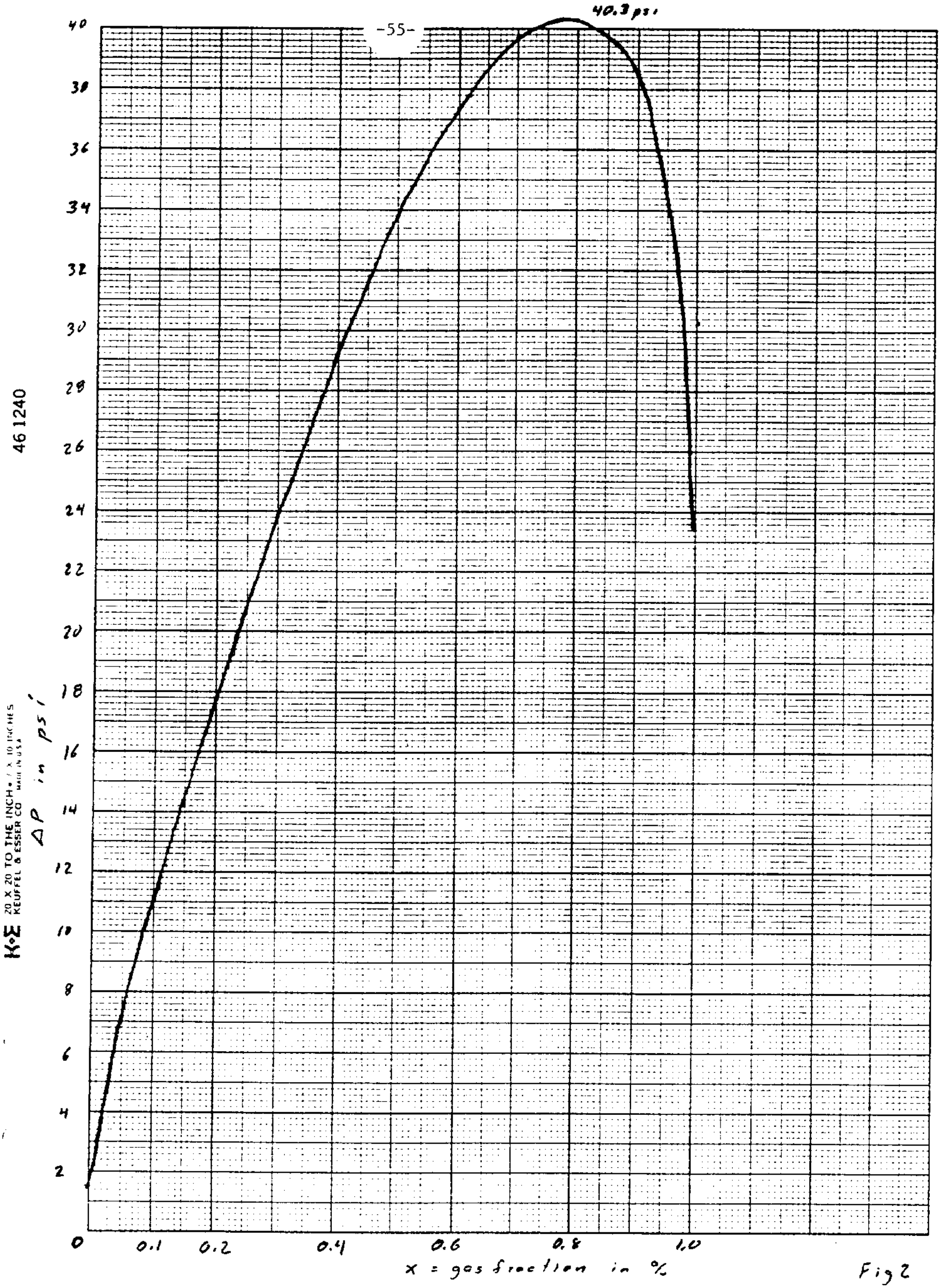

40.3 psi
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
ΔP in psi
0.1
0.2
0.4
0.6
0.8
1.0
x = gas fraction in %
K+E 20 X 20 TO THE INCH • 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 1240

Fig 2

SSC DETECTOR SOLENOID DESIGN NOTE #18

TITLE: Quench Safety I: Choice of Current Densities

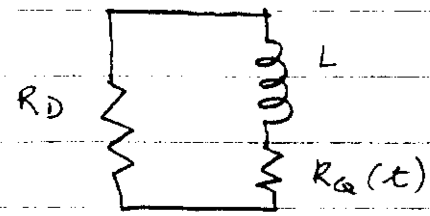
AUTHOR: R.W. Fast

DATE: Apr. 6, 1988

CONCLUSION

A 4-m coil module, with a conductor current density of ~3000 A/cm2, will be safe against a quench and will have a sufficiently low surface heat flux. A 2-m module with ~5000 A/cm2 will be safe on quench, but the surface heat flux is a bit high. A current density of 1600 to 1800 A/cm2 will permit the coil modules, of whatever size, to be electrically connected into 8-m units.

I. Calculate the maximum current density that is consistent with quenching safely.



If we ignore the mutual inductance between coil modules and if $R_D > R_Q(t)$, the current decay is:

$$I(t) = I_o e^{-\frac{R_D}{L} t} \; ; \quad J(t) = J_o e^{-\frac{R_D}{L} t}$$

and

$$\int_0^\infty J^2(t)\, dt = \frac{1}{2} J_o^2 \frac{L}{R_D} = U(\Theta_m) \quad \text{(Wilson, p 219)}$$

Solving for J_o:

$$J_o^2 = \frac{2\, U(\Theta_m)}{L/R_D} \; ; \quad J_o = \sqrt{\frac{2\, U(\Theta_m)}{L/R_D}}$$

Now let $\Theta_m = 100\,K$, with $RRR \sim 100$, ($\rho_{cu} = 10^{-10}\ \Omega\text{-}m$), then

$$U(\Theta_m) = 7 \times 10^{16}\ A^2\text{-}s\text{-}m^{-4}$$

and

$$J_o(\Theta_m = 100K) = \frac{3.74 \times 10^8}{\sqrt{L/R_D}} \quad A\text{-}s^{1/2}\text{-}m^{-2}$$

If we limit the terminal voltage to 500V then

$R_D = 0.1\,\Omega$ for a 5kA magnet, independent of L.

Solving for J_0(100K) for different inductances (coil module lengths):

Nominal coil length (m)	L^* (H)	R (Ω)	J_{cond} (100K) (A/cm²)
8	49.6	0.1	1679
4	18.1	0.1	2780
2	5.75	0.1	4932

* For 9-m diameter; see DN #17.

II. Compare current densities of recent large SC magnets

Magnet	Bmax (T)	Jcond (A/cm²)	Max temp Θ_m (K)
Tohoku B.C.	4.9	6670	?
CCM	2.8	9568	?
15' B.C.	4.5	3700	?
LCT/GD	8.0	4075	200
LCT/Japan	8.0	3027	?
MFTF-Y-Y	7.7	4978	210
MFTF-Solen.	3.2	4586	124

III. Surface heat flux at $J_{cond} = 3000\ A/cm^2$ and $I = 5\ kA$ (a 4-m coil module)

$$A_{cond} \sim A_{cu} = \frac{5000}{3000}\ cm^2 = 1.7\ cm^2$$

If the conductor were square, $a = b = 1.3$ cm

$$\text{The Heat Flux} = \frac{I^2 \rho}{\gamma(ab)\,2(a+b)}$$

where γ = fraction of surface wetted

Parameter	MFTF-S	4-m Det. Solen.	2-m Det. Solen.
Current (A)	2866	5000	5000
Conductor (cm × cm)	1.25 × 0.5	1.3 × 1.3	1.0 × 1.0
A_{cond} (cm^2)	0.625	1.7	1.0
J_{cond} (A/cm^2)	4586	3000	5000
ρ (Ω-cm)	10^{-8}	10^{-8}	10^{-8}
$I^2\rho / 2ab(a+b)$ (W/cm^2)	0.0375	0.0283	0.0625
$I^2\rho / 2(\gamma ab)(a+b)$ (W/cm^2)	0.154 (pg 11-16)	0.118	0.260
γ	0.24	0.24	0.24

IV. Remarks

For a maximum hot-spot temperature of 100K, the conductor current density (3000 A/cm²) is low in comparison with other cryostable magnets, but not absurdly so. The surface heat flux (0.0283 W/cm²) is 25% less for a 4-m module than for METF solenoids, again not absurd.

A more detailed quench analysis would probably suggest a higher current density. The coupling of the circuits through the mutual inductance should be considered.

V. Conclusion

A 4-m coil module, with a conductor current density of ~3000 A/cm², will be safe against a quench and will have a sufficiently low surface heat flux. A 2-m module with ~5000 A/cm² will be safe on quench, but the surface heat flux is a bit high.

SSC DETECTOR SOLENOID DESIGN NOTE #20

TITLE: Charge/Discharge Times, Eddy Current Power and Energy

AUTHOR: R.W. Fast

DATE: Apr. 26, 1988

SUMMARY: A charge voltage of ~30 V will permit the magnet to be charged in about 3 hours with an eddy current power of a few watts in each 2-m coil/LHe vessel module. The eddy current heat load during a fast dump (R_{FD} = 0.1 Ω, τ = 600 s) is 645 W per 2-m coil module, which would probably quench the module. I propose that the coil be discharged through R_{FD} only if a quench is detected; otherwise it would be discharged through a slow dump resistor (R_{SD} = 0.01 Ω, τ = 6000 s, P_E'(max) = 6.5 W).

I. Charge time

During a charge

$$V_L = \text{voltage across coil}$$
$$= L \, dI_L(t)/dt$$

Assuming a constant voltage charge from $I_L(t) = 0$ to 5 kA and L the inductance of an 8-m assembly (four, 2-m coils in series electrically),

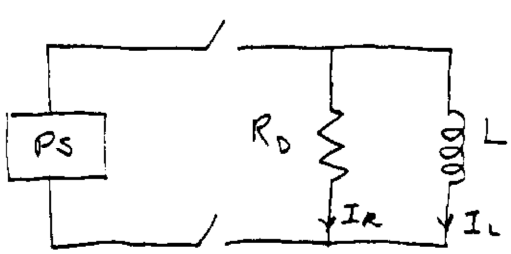
$$t_{chg} = L\, I_L(t_{chg})/V_L = (60\,H)(5000\,A)/V_L$$
$$= 30 \times 10^4 \, s/V_L$$

$$P_{PS}(t) = \text{power drawn from power supply}$$
$$= V_L \left[I_L(t) + I_R(t) \right]$$

$$\text{At } t = 0: \; I_L(0) = 0, \quad I_R(0) = V_L/R_D$$
$$t = t_{chg}: \; I_L(t_{chg}) = 5\,kA, \quad I_R(t_{chg}) \sim 0$$

$$P_{PS}(max) = V_L \, I_L(t_{chg})$$

Circuit



$L = 60\,H$ (8-m unit)

V_L (V)	P_{PS} (max) (kW)	dI_L/dt (A/s)	t_{chg} (s)	(h)
15	75	0.25	20×10^3	5.6
20	100	0.33	15×10^3	4.2
30	150	0.50	10×10^3	2.8
60	300	1.0	5×10^3	1.4

II. Discharge time - fast dump

$R_{FD} = 0.1\,\Omega$ to limit discharge to 500 V across terminals

$$I_L(t) = I_L(0)\, e^{-\frac{R_{FD}}{L}t}$$

$$= (5000\,A)\, e^{-t/600}$$

$$V_L = I_L(t) R_{FD}$$ (No quench, or for $R_{FD} > R_a$)

$$= (500\,V)\, e^{-t/600}$$

III. Eddy current heating in helium vessel during charge

The changing current in the coil induces a voltage $V_E = M\, dI_L/dt$ in the helium vessel and hence an eddy current $I_E = V_E/R_E$.

The power dissipated in the vessel due to this eddy current

$$P_E(t) = V_E^2/R_E = (M\, dI_L/dt)^2/R_E$$

where

M = the mutual inductance between the coil and the helium vessel

R_E = circumferential resistance of the helium vessel

To estimate R_E of 2-m module

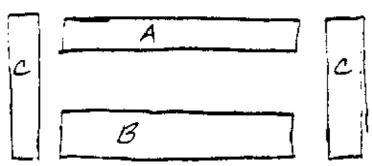


Plate A : $1880 \times 35\ mm^2$

B : $1880 \times 50\ mm^2$

C : $244 \times 35\ mm^2$

A_E = cross section of helium vessel

$$= \left((1880 \times 35) + (1880 \times 50) + 2(244 \times 35) \right) \times 10^{-6}\, m^2$$

$$= 0.1769\ m^2$$

$$R_E = \frac{(\rho_{SS} @ 4.5K)(\text{vessel circumference})}{A_E}$$

$$= \frac{(50 \times 10^{-10}\ \Omega\text{-}m)^{*}\,(9.5\pi\ m)}{0.1769\, m^2}$$

$$= 84.4\ \mu\Omega$$

* From S.C. Machinery Handbook for 304L at 4.5K

To estimate M

$$M = \text{flux linked by the vessel per unit coil current}$$

$$= \frac{\Phi(I_{L\,max})\ (1\ \text{turn})}{I_{L\,max}}$$

$$\sim \frac{(2T)(\frac{1}{4}\pi\, 9.5^2)\,(1)}{5000}$$

$$= 0.028\ H$$

To estimate P_E during charge (2-m module)

$$P_E(t) = (0.028)^2 (dI_L/dt)^2 / 84.4 \times 10^{-6}$$

$$= 9.3\,(dI_L/dt)^2\ \ W$$

		For 2-m module	
V_L (V)	dI_L/dt (A/s)	P_E (W)	E_E (kJ)
15	0.25	0.58	11.6
20	0.33	1.01	15.2
30	0.50	2.33	23.3
60	1.0	9.3	46.5

where E_E = energy absorbed by helium vessel during charge

$$= P_E\, t_{chg}$$

IV. Eddy current heating during fast discharge

$$P_E'(t) = \text{power dissipated during fast discharge - 2-m module}$$

$$= (M\ dI_L/dt)^2 / R_E$$

$$\frac{dI_L}{dt} = \frac{d}{dt}\left(I_0\ e^{-t/600} \right)$$

$$= -\frac{I_0}{600}\ e^{-t/600}$$

$$P_E'(t) = \frac{M^2 I_0^2}{600^2 R_E}\ e^{-2t/600}$$

$$P_E'(max) = \left[\frac{(0.028)(5000)}{600}\right]^2 / R_E$$

= 645 W per 2-m module

$$E_E'(t) = \left(\frac{MI}{600}\right)^2 \frac{1}{R_E} \int_0^\infty e^{-2t/600}\,dt$$

$$= \left(\frac{MI}{600}\right)^2 \frac{1}{R_E}\ (300) = 300\ P_E'(max)$$

= 194 kJ per 2-m module

This heat load appears to be unacceptably large for a routine discharge, i.e. it may cause the coil to quench. Therefore the coil will be discharged through the $0.1\,\Omega$ resistor only if a quench is detected. A "slow" discharge resistor, $R_D' = 0.01\,\Omega$, could be used to reduce the eddy current heat load to 6.5W during discharge. The energy deposited in the vessel during a slow dump is 19.4 kJ.

SSC DETECTOR SOLENOID DESIGN NOTE #24

TITLE: Conceptual Design of a Superconducting Solenoid for a Magnetic SSC Detector *(Paper delivered at the 12th International Cryogenic Engineering Conference and submitted for publication in the conference proceedings.)*

AUTHOR: R.W. Fast et al

DATE: July 13, 1988

 Paper delivered at the 12th International Cryogenic Engineering Conference and submitted for publication in the conference proceedings.

CONCEPTUAL DESIGN OF A SUPERCONDUCTING SOLENOID FOR A MAGNETIC SSC DETECTOR

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The conceptual design of a large superconducting solenoid suitable for a magnetic detector at the Superconducting Super Collider (SSC) has begun at Fermilab. The magnet will provide a magnetic field of 2 T over a volume 8 m in diameter by 16 m long. The particle-physics calorimetry will be inside the field volume and so the coil will be bath cooled and cryostable; the vessels will be stainless steel. Predictibility of performance and the ability to safely negotiate all probable failure modes, including a quench, are important items of the design philosophy. Although the magnet is considerably larger than existing solenoids of this type and although many issues of manufacturability, transportability and cost have not been completely addressed, our conceptual design has convinced us that this magnet is a reasonable extrapolation of present technology.

INTRODUCTION

A large solenoid is being considered as part of a detector (Fig. 1) for experiments performed on the Superconducting Super Collider (SSC). The conceptual design of a solenoid suitable for a detector has begun at Fermilab and some preliminary specifications have been developed. The field volume proposed to perform proton-proton experiments with the SSC is 8 m in diameter and 16 m long; a field of 1.5 to 2 T is desired. The magnet will have an iron flux return yoke at a field of 1.5 T. A significant feature of this detector is that all the calorimetry will be inside the bore of the magnet. This feature impacts the design of both the calorimeter support system and the superconducting coil in a major way. Another feature of the detector that influences the design of the magnet is its location in a detector hall 100 to 150 m below the surface.

The calorimeter and central tracking chamber for the SSC detector will occupy the entire field volume and will weigh about 5000 tonnes. This weight could be transmitted to the floor of the detector hall either through the vacuum vessel of the magnet coil or through an independent support structure. The calorimeter will be split at the longitudinal center for instrumentation cabling. Taking advantage of this, we have designed two independent calorimeter support structures, each 8 m long, supported to the iron yoke at both ends. The stainless steel weldment consists of two cylinders with a web of trusses between; it has a radial thickness of 250 mm. The calorimeter modules will rest on rails along each side of the structure and can be installed from either or both ends.

Because the calorimetry is inside the bore of the solenoid it is not necessary that the coil and vessels be thin in terms of radiation and absorption lengths. We therefore chose a cryostable, bath-cooled coil, able to withstand quenching without damage. The conductor is copper stabilized; the helium and vacuum vessels are stainless steel. We have located as many of the active elements as possible in an aboveground service building; the power supply, dump switches, pumps and control valves.

For the purpose of this conceptual study, we have adopted a fabrication and assembly scenario as follows: (1) The coil is wound in 2-m long modules about a vertical axis, each module forming a liquid helium vessel. (2) Four coil modules are stacked vertically and bolted together to form an 8-m cold mass; electrical interconnections are made in liquid helium pipes along the top. (3) The outer vacuum shell, with a liquid nitrogen cooled thermal shield attached, is lowered over the cold mass and the supports attached to each end. (4) The inner vacuum shell-thermal shield subassembly is vertically inserted and the flat annular heads welded in place. (5) The assembly is then rotated to a horizontal axis and a 5000-L helium storage dewar attached. (6) The two 8-m assemblies are cryogenically and electrically tested. (7) The 500-tonne assemblies are then lowered into the detector hall and secured to the iron yoke in a way that allows for a $20^{\circ}C$ thermal contraction of the 8-m vacuum vessel. Figure 2 is a cross section of the coil and cryostat.

CONDUCTOR AND QUENCH PROTECTION

The inner diameter of the superconducting coil was chosen as 9.5 m, which provides adequate space for vessel shells, insulating vacuum and clearance to the calorimeter support structure. We chose to operate at a current of 5 kA and to electrically connect four 2-m coil modules in series with superconducting bus. Table 1 gives some of the operating parameters of the magnet. We believe that it is essential that the coil survive quenches without damage. We will provide this protection through the use of an external fast dump resistor and by specifying a rather low conductor current density. The parameters associated with a quench are given in Table 2. Because of the large heat load due to eddy current in the helium vessel, a fast dump will be initiated only when a quench is detected. A normal discharge will be through a slow dump resistor, with the power supply reversed so the discharge is at constant voltage.

We selected a built-up conductor with a Nb-Ti/Cu monolith or cable soldered into additional copper stabilizer. The conductor dimensions are 16 mm x 18 mm. With a short sample rating of 10 kA at 3 T and 4.5 K and a current density in the superconductor of 3×10^5 A/cm^2, the copper to superconductor ratio will be about 90. The surface heat flux with a copper RRR of 100 and 25% surface wetting is 0.05 W/cm^2.

COIL-HELIUM VESSEL MODULE

Each 2-m coil module has seven layers of 93 turns for a total of 651 turns. We chose G-10 buttons on a string as the turn-to-turn insulation, slotted G-10 sheets between layers and slotted and channeled G-10 and Kapton as insulation to ground, giving a packing factor of 0.65. The conductor is layer wound the "easy" way, beginning at the outer layer, on the inside of a coil form which makes up the outer shell and flat heads of the helium vessel. The winding fixture applies the radial preload; compression bars at one end of the coil apply the axial preload. The coil module will be closed by welding the inner shell to the coil form.

The 2-m coil-helium vessel module is designed for a gauge pressure of 0.7 MPa (100 psi). The inner and outer shells are also designed for the axial electromagnetic force. The radial electromagnetic pressure of 1.6 MPa (230 psi) is partially resisted by the conductor and partially by the outer shell, depending on the stiffness of the coil. The vessel is adequately relieved for a loss of insulating vacuum or a quench.

We propose a thermosiphon to provide a flow of liquid helium through the coil package. Each of the coil-helium vessel modules has a supply line from the storage dewar leading to the bottom of the module. These lines are very well insulated so they contain only liquid helium. Two return and vent lines lead from the top of each module to the storage dewar.

SUPPORTS

When installed in the iron yoke, each 8-m cold mass has an axial body force on it which depends on the geometry of the end wall and reentrant end plug. For the one coil configuration studied thus far, calculations with a cylindrically symmetric iron flux return indicate that this force is a minimum without reentrant iron, being about 7.3 MN (1.64×10^6 lb) toward the symmetry plane. The axial force constant is 149 MN/m (8.5×10^5 lb/in) and the radial force constant is 8.8 MN/m (5×10^4 lb/in); from experience with the solenoid at the Collider Detector-Fermilab we have chosen an axial and radial misalignment or the equivalent, due to non-uniform iron properties, of 25 mm. The support system is not designed for independent charging or operation of the two 8-m coil modules; bumpers limit axial travel if only one module is energized because of a control system failure.

The system to support the 8-m cold mass in the vacuum vessel could have either separate elements to react the axial and radial force components or combined-function elements. We have tentatively chosen the latter. We believe that the supports should be metallic, possibly Inconel 718, with spherical bearings on each end. The attachment points on the vacuum vessel are near the ends to avoid carrying the electromagnetic forces through the vacuum shells. Each support will have an intercept cooled by a forced flow of subcooled liquid nitrogen at about 80 K and a liquid helium intercept in a thermosiphon circuit independent of the coil module circuit.

REFRIGERATION SYSTEM

The refrigeration plant is located at ground level, with vacuum jacketed lines going down to the detector hall. The helium plant supplies liquid to the storage dewars on top of the detector. Because of the depth of the detector hall a cold compressor is used to maintain the liquid in the dewars at about 30 kPa (4.5 psig) and 4.5 K. For the proposed electrical insulation scheme and resulting flow paths through the coil, the helium supply and return lines can be sized to provide a thermosiphon flow rate through each 2-m coil module of at least 23 g/s with a return gas fraction less than 1% by weight. The flow rate through the support intercept circuit will be about 50 g/s at a gas fraction of 7% or less. The total expected heat load to the helium system is 360 W plus 36 L/h (540 W equivalent). The 4.5-K helium refrigerator will probably have a capacity of 1600 to 1800 W. Sub-cooled liquid nitrogen at an average temperature of 83 K is forced through the various shield and intercept circuits by a circulator pump at detector hall level. The total heat load to the nitrogen system is expected to be 6 kW.

The total cold mass (two 8-m assemblies) is about 800 tonnes; an overall cooldown time of about two weeks is desired. A separate cooldown refrigerator, consisting of a helium to liquid nitrogen heat exchanger and a turboexpander, providing 400 g/s of 55 K helium gas can achieve this.

CONCLUSIONS

It appears that the diameter of this detector solenoid will preclude its fabrication at a vendor's off-site facility, although some components and subassemblies, e.g. the coil form, could possibly be fabricated elsewhere and shipped by barge and helicopter. A large hall will be necessary on the SSC site for the coil winding, the closure welding of the coil-helium vessel modules, the assembly of the 8-m modules and the testing with the refrigerator. The hall will require at least a 100 tonne crane with a hook height of at least 12 m. The access shaft from the surface down 100-150 m to the detector hall will have to be about 14 m in diameter.

We concluded, as a result of this preliminary study, that the magnet is a reasonable extrapolation of superconducting magnet technology. Additional work on techniques for its manufacture including cost and time estimates are still needed. The optimization of parameters through more detailed study might result in a more cost-effective design, however at this point in the effort we see nothing that would preclude the construction of such a magnet.

ACKNOWLEDGEMENTS

This work was sponsored by Universities Research Association, Inc. under contract with the U.S. Department of Energy. The authors would like to thank R.W. Baldi and R.A. Johnson of General Dynamics/Space Systems Division for providing us with engineering reports on the MFTF solenoids which were very useful to us in developing the concepts for this magnet.

Table 1. Operating Parameters

Center-line axial field = 2 T
Operating current = 5 kA
Total stored energy at 2 T = 1 GJ
Charge time = 100 min with 50 V
Slow dump resistor = 0.01 Ω
Operating temperature = 4.5 K

Table 2. Quench Parameters

Self-inductance = 60 H
Fast dump voltage = 500 V
Fast dump resistor = 0.1 Ω
Maximum hot spot temperature = 100 K
Stabilizer current density = ~~1756~~ A/cm²
Fast dump eddy current heat load = 650 W

Typographical error, should be 1736 A/cm²

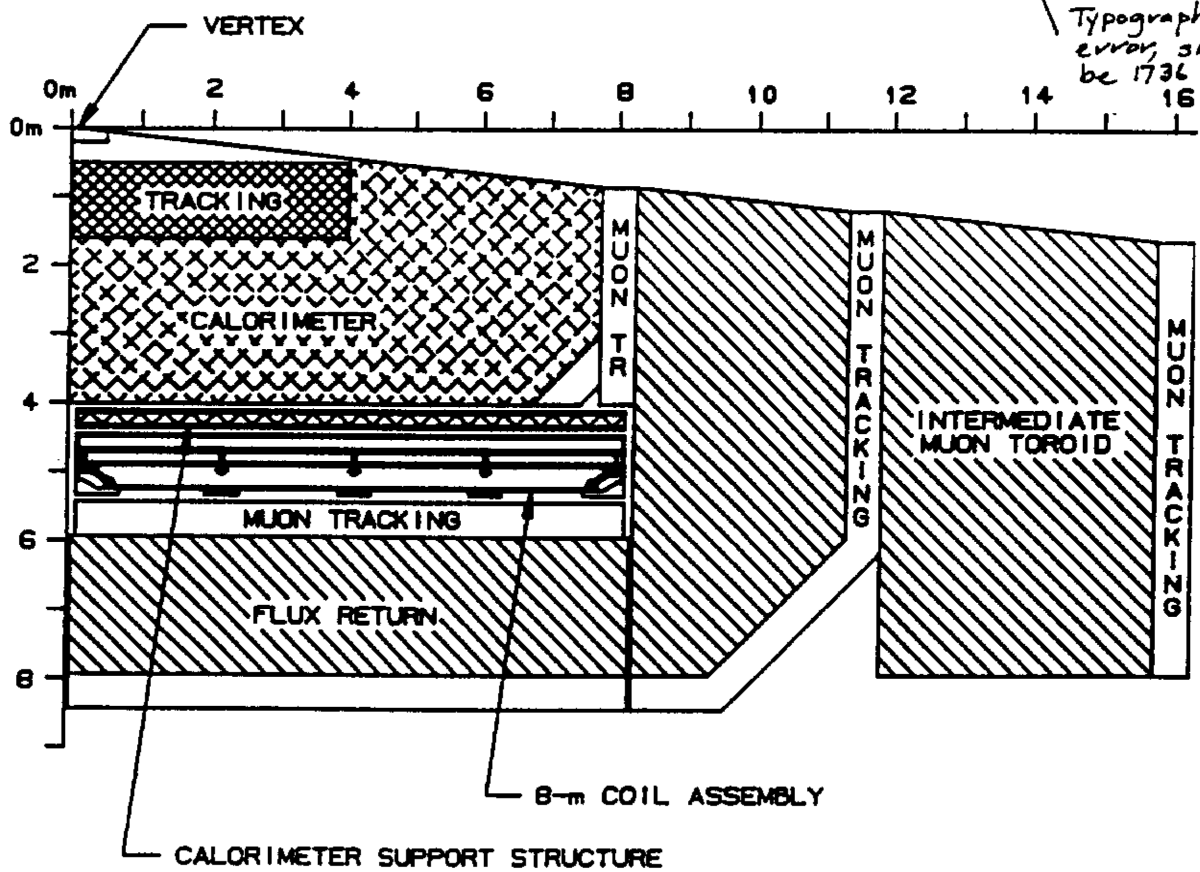


Fig. 1 SSC detector with large superconducting solenoid.

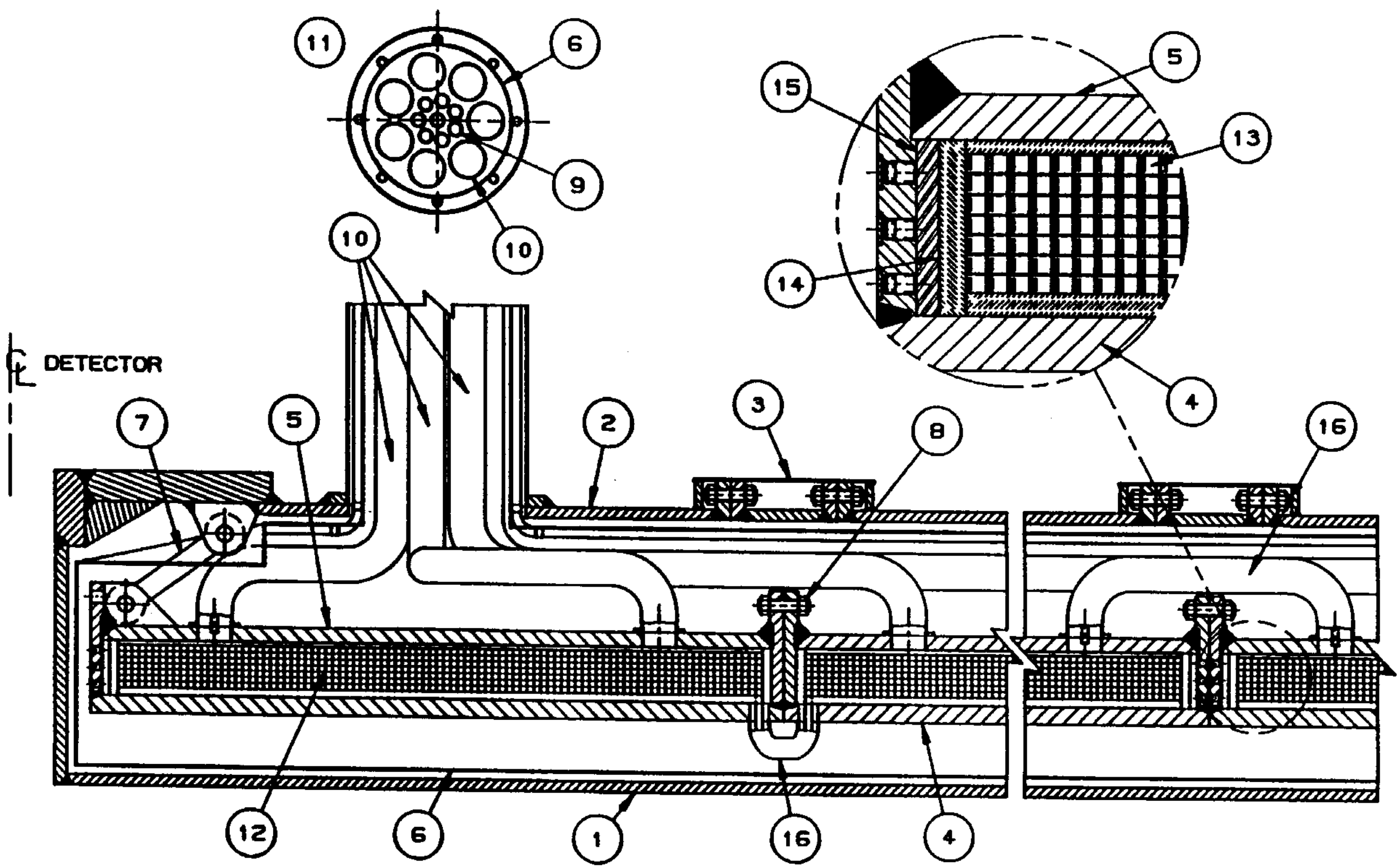


Fig. 2 Axial cross section of coil, helium and vacuum vessels: 1, inner and 2, outer vacuum shell; 3, assembly joint (if required); 4, inner and 5, outer helium vessel shell; 6, radiation shield; 7, cold mass support; 8, coil module attachment; 9, liquid helium supply pipe; 10, helium return/vent pipe; 11, chimney to storage dewar; 12, coil winding; 13, conductor; 14, G-10 insulation; 15, axial preload bar; 16, electrical interconnect pipe.

SSC DETECTOR SOLENOID DESIGN NOTE #25

TITLE: Conductor and Coil Parameters for Coils in Series Electrically; Eddy Current Heating

AUTHOR: R.W. Fast

DATE: Aug. 11, 1988

SUMMARY: This coil design has 93 turns per layer and 7 layers. The conductor is 18 mm axially x 26 mm radially. The conductor current density is 1068 A/cm^2, giving a maximum adiabatic hot spot temperature of 100 K. The eddy current heat loads are given below.

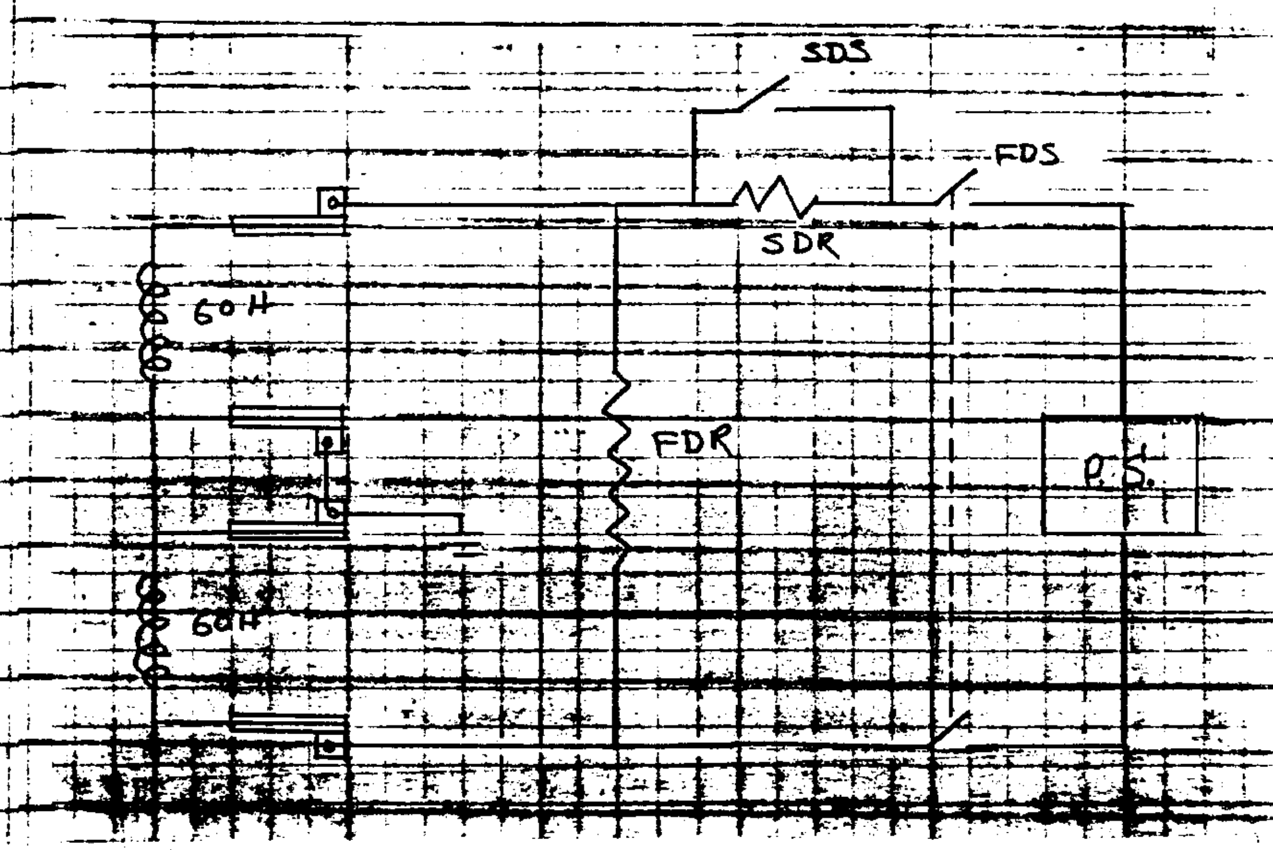
Linear Charge or Slow Dump Heat Load

Voltage	Chg/Dischg Time	P(He ves) 8m	P(He ves) 2x8m	P(coil) 8	P(coil) 2x8m	P(total) 8m	P(total) 2x8m
(V)	(s)	(W)	(W)	(W)	(W)	(W)	(W)
50	12000	6.5	13.0	6.9	13.8	13.4	26.8
100	6000	25.8	51.6	27.6	55.2	53.4	106.8

Fast Dump Heat Load

τ	P(He ves) 8m	P(He ves) 2x8m	P(coil) 8m	P(coil) 2x8m	P(total) 8m	P(total) 2x8m
(s)	(W)	(W)	(W)	(W)	(W)	(W)
1200	645	1290	688	1376	1333	2666

I. Electrical Circuit



Quench - Fast Dump criteria:

1. Fast dump voltage - all points in coil less than 250V to ground during fast dump
2. Quench behavior - maximum adiabatic hot spot temperature = 100K.

II. Conductor Design

From DN # 18, for $\theta_m = 100K$ and RRR ~ 100

$U(\theta_m) = 7 \times 10^{16}\ A^2 - s^2 - m^{-4}$

and $J_o(\Theta_m = 100K) = \dfrac{3.74 \times 10^8}{\sqrt{L/FDR}}$ $A\text{-}s^{1/2}\text{-}m^{-2}$

With $L = 120\,H$, $FDR = 0.1\,\Omega$ the req'd $J_o(100K) = 1080\ A/cm^2$.

For a conductor which is 18 × 26 mm the actual $J_o = 5000A/1.8 \times 2.6\ cm^2 = 1068\ A/cm^2$, so I chose these conductor dimensions, 18 mm is along the axis, i.e. conductor wound the "hard" way.

III. Coil Design

Since the conductor axial is unchanged from the design in DN #19A, the number of turns per layer is unchanged at 93.

The number of layers is the same (7), but the radial extent of the coil is larger by 7 cm (2 3/4").

The mass of conductor per 2-m coil module increases from 50.6 Mg (DN #21) to $(26/18)(50.6) = 73$ Mg (metric tons).

IV. Coil Charging

Charge time depends on power supply voltage:

Chg Voltage (V)	dI_L/dt (A/s)	Chg time (s)	(h)
50	0.417	12000	3:20
100	0.833	6000	1:40

Eddy current heating in helium vessel:

From DN#20

$$P(\text{Chg, He ves}) = \left(M \, dI_L/dt\right)^2 / R(\text{He ves})$$

where I_L = current in coil

DN#20 has a calculation of M & R(He ves):

$M = 0.028$ H

R (2-m He ves) = 84.4 $\mu\Omega$

so R(8-m He ves) = 21.1 $\mu\Omega$

Chg Voltage (V)	dI_L/dt (A/s)	~~P(chg, He vessel)~~ 8-m (W)	2 × 8-m (W)
50	0.417	6.46	12.92
100	0.833	25.8	51.6

Eddy current heating in conductor:

To get an estimate of this, I used the equation from the CDF Design Report (p. 50)

$$P(\text{coil}) = \frac{N_t}{R_c}\left(A_{eff}\,\frac{dB}{dt}\right)^2$$

where N_t = number of turns on coil
R_c = effective resistance of one turn
A_{eff} = " area of conductor per turn across which flux crosses

For a 2-m coil module (DN #19A)

N_t = 651

$$R_c = \frac{(10^{-10}\,\Omega\cdot m)(9.5\,\pi\, m)}{(18\times10^{-3} m)(26\times10^{-3} m)}$$

$= 6.4\ \mu\Omega$

$A_{eff} = (9.5\,\pi\, m)(26\, mm) = 0.78\ m^2$

So $P(\text{coil}) = 61.9\times10^{6}\ (dB/dt)^2$

And

Chg Voltage (V)	Chg time (s)	B_o (T)	dB/dt (T/s)	P(coil) 8-m (W)	P(coil) 2×8-m (W)
50	12000	2	1.67×10^{-4}	6.90	13.8
100	6000	2	3.34×10^{-4}	27.6	55.2

Total heat load - charge

Chg Voltage (V)	~~P(Heves)~~ 8m (W)	2x8m (W)	~~P(coil)~~ 8m (W)	2x8m (W)	~~P(total)~~ 8m (W)	2x8m (W)
50	6.5	13.0	6.9	13.8	13.4	26.8
100	25.8	51.6	27.6	55.2	53.4	106.8

V. Slow Dump

Discharge time:

Reversing the power supply will give a constant-voltage discharge. The SDR is sized such that 5000A x SDR = P.S. voltage.

Dischg voltage (V)	SDR (Ω)	dI_L/dt (A/s)	Dischg time (s)	(h)
50	0.01	−0.417	12000	3:20
100	0.02	−0.833	6000	1:40

Eddy current heating in He vessel

Same equation as for charging:

Dischg voltage (V)	dI_L/dt (A/s)	P(SD, He vessel) 8m (W)	2x8m (W)
50	−0.417	6.46	12.92
100	−0.833	25.8	51.6

Eddy current heating in conductor
same as for charge:

Dischg voltage	$P(SD, coil)$ 8 m	2 x 8 m
(V)	(W)	(W)
50	6.90	13.8
100	27.6	55.2

Total heat load — slow dump

Dischg voltage	$P(SD, He ves)$ 8 m	2 x 8 m	$P(SD, coil)$ 8 m	2 x 8 m	$P(SD, total)$ 8 m	2 x 8 m
(V)	(W)	(W)	(W)	(W)	(W)	(W)
50	6.5	13.0	6.9	13.8	13.4	26.8
100	25.8	51.6	27.6	55.2	53.4	106.8

VI. Fast Dump

Discharge time:

$$\tau \lesssim L/FDR = 120/0.1 = 1200\ s$$

Eddy current heating in He vessel

$$P^{8\text{-}m}_{max}(FD, He\ ves) = \left(\frac{M I_0}{\tau}\right)^2 / R(He\ ves)$$

$$= \left(\frac{0.028 \times 5000}{1200}\right)^2 / 21.1 \times 10^{-6}$$

$$= 645\ W$$

Eddy current heating in conductor

$$P(FD, \overset{2m}{coil}) = 61.9 \times 10^6 \left(dB/dt\right)^2$$

$$= 61.9 \times 10^6 \frac{B_o^2}{\tau^2} e^{-2t/\tau}$$

$$P_{max}(FD, 2m\ coil) = (61.9 \times 10^6)\left(\frac{2}{1200}\right)^2$$

$$= 172\ W$$

τ (s)	B (T)	P_{max}(FD, coil) 8m (W)	2 x 8m (W)
1200	2	688	1376

SSC DETECTOR SOLENOID DESIGN NOTE #26

TITLE: SSC Detector Solenoid *(Paper delivered at the 1988 Applied Superconductivity Conference and accepted for publication in the conference proceedings.)*

AUTHOR: R.W. Fast et al

DATE: Sept 26, 1988

Presented At ASC-88

SSC DETECTOR SOLENOID

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Abstract

A detector utilizing a superconducting solenoid is being discussed for the Superconducting Super Collider (SSC). A useful field volume of 8 m diameter x 16 m length at 1.5-2 T (~1 GJ at 2T) is required. It has been decided that all of the particle physics calorimetry will be inside the bore of the solenoid and that there is no need for the coil and cryostat to be "thin" in radiation lengths. An iron yoke will reduce the excitation required and will provide muon identification and a redundant momentum measurement of the muons. We have developed a conceptual design to meet these requirements. The magnet will use a copper-stabilized Nb-Ti conductor sized for a cryostable pool boiling heat flux ~0.025 W/cm^2. A thermosiphon from a storage vessel above the cryostat will be used to prevent bubble stagnation in the liquid helium bath. The operating current, current density, coil subdivision and dump resistor have been chosen to guarantee that the coil will be undamaged should a quench occur. The axial electromagnetic force will be reacted by metallic support links; the stainless steel coil case will support the radial force. The 5000 metric tons of calorimetry will be supported from the iron yoke through a trussed cylindrical shell structure separate from the cryostat. The coil and case, radiation shield and stainless vacuum vessel would be fabricated and cryogenically tested as two 8-m sections. These would be lowered into the underground experimental hall and installed into the iron flux return yoke to provide the required 16-m length.

Introduction

The SSC will have six interaction regions which, depending on the laboratory location, could be as deep as 120 meters. A large superconducting solenoid is being considered as a part of a detector facility for one of the interaction halls. Figure 1 is the SSC detector. The calorimetry and central tracking chambers, which will be located inside the solenoid, require a field volume 8 m in diameter by 16 m long. The field in the bore will be 2 T; the field in the iron flux return yoke will be ~1.5 T. Locating the calorimetry internal to the solenoid eliminates the need to have a "thin" coil and cryostat in terms of radiation lengths; we may therefore employ a cryostable pool boiling coil.

The required field volume will be provided by two solenoids, each 9.5 m in diameter and 8 m in length, connected in series electrically with a common power supply. Each 8-m unit will contain four identical 2-m long liquid helium/coil modules. The modules are mechanically connected and share a common vacuum vessel. Helium is supplied by thermosiphons to an 8-m assembly from a storage vessel located on top of the iron, with each of the four modules having its own helium supply and return piping.

The calorimetry and flux return iron will be split at the longitudinal center and the halves can be moved independently; therefore, we will use two 8-m support structures to support the 5000 metric tons of calorimetry and central tracking chamber. There are notches in the iron for hangers for the supports and for instrumentation cables. The support structures are immediately inside the solenoids but are completely independent of the cryostat and vacuum shell. The ends of each structure will be supported from the iron. The support structures, consisting of concentric stainless steel cylinders with a trussed web, having a radial thickness of 25 cm are expected to have a deflection of ~3 cm when loaded with the tracking chambers and calorimetry. The calorimeter will rest on rails and can be inserted from either end.

Quench Protection

Four 2-m modules are connected in series with the superconducting bus between the modules being in liquid helium filled interconnecting pipes. It is essential that the coil survive quenches without damage and to this end a low current density and an external fast dump resistor were chosen. This resistor was chosen to be 0.1 Ω to limit the discharge voltage to 500 V across the terminals. The eddy current heating in both the coil and helium vessel during a fast dump is expected to be ~1300 W for an 8-m assembly. This might be sufficient to quench the coil and so the discharge will be through the fast dump resistor only if a normal zone is detected. The highest temperature reached in the coil due to a quench will be 100 K. A discharge for any other reason will be through a 0.02 Ω slow dump resistor with the power supply reversed to maintain a constant discharge voltage. The routine charge or discharge time, with 100 V across the terminals, would be 100 min and the eddy current heat load would be 26 W per 8-m assembly. Figure 2 is the electrical schematic.

Conductor and Coil Specifications, Winding and Assembly Scheme

The superconductor will be copper stabilized Nb-Ti wire which has a short sample current of 10 kA at 3 T and 4.5 K. This wire will be soldered into additional copper stabilizer. The final conductor will be 26 x 18 mm and will have a copper to superconductor area ratio of 146 to 1. The operating current will be 5000 A resulting in a current density of 1.56 x 10^5 A/cm^2 in the superconductor and 1068 A/cm^2 overall. The surface heat flux, with 25% wetting and a RRR of 100, is 0.025 W/cm^2.

There are seven conductor layers having a total of 651 turns in each 2-m coil module. Since the forces are radially outward, the coil will be wound starting with the outside layer, using the outer shell and flat annular heads as a coil form. Insulation will consist of G-10 buttons between turns, slotted G-10 sheets between layers and slotted G-10 and Kapton adjacent to the helium vessel. The packing factor will be 74% with 13% being helium space.

Each 2-m coil module will be designed in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code for an internal pressure differential of 0.8 MPa (116 psia) and will be adequately relieved for a loss of insulating vacuum or a quench of the coil. The axial electromagnetic force will be transmitted through the shells to the supports, and the radial force will be resisted by both the conductor and outer shell.

Manuscript received August 22, 1988

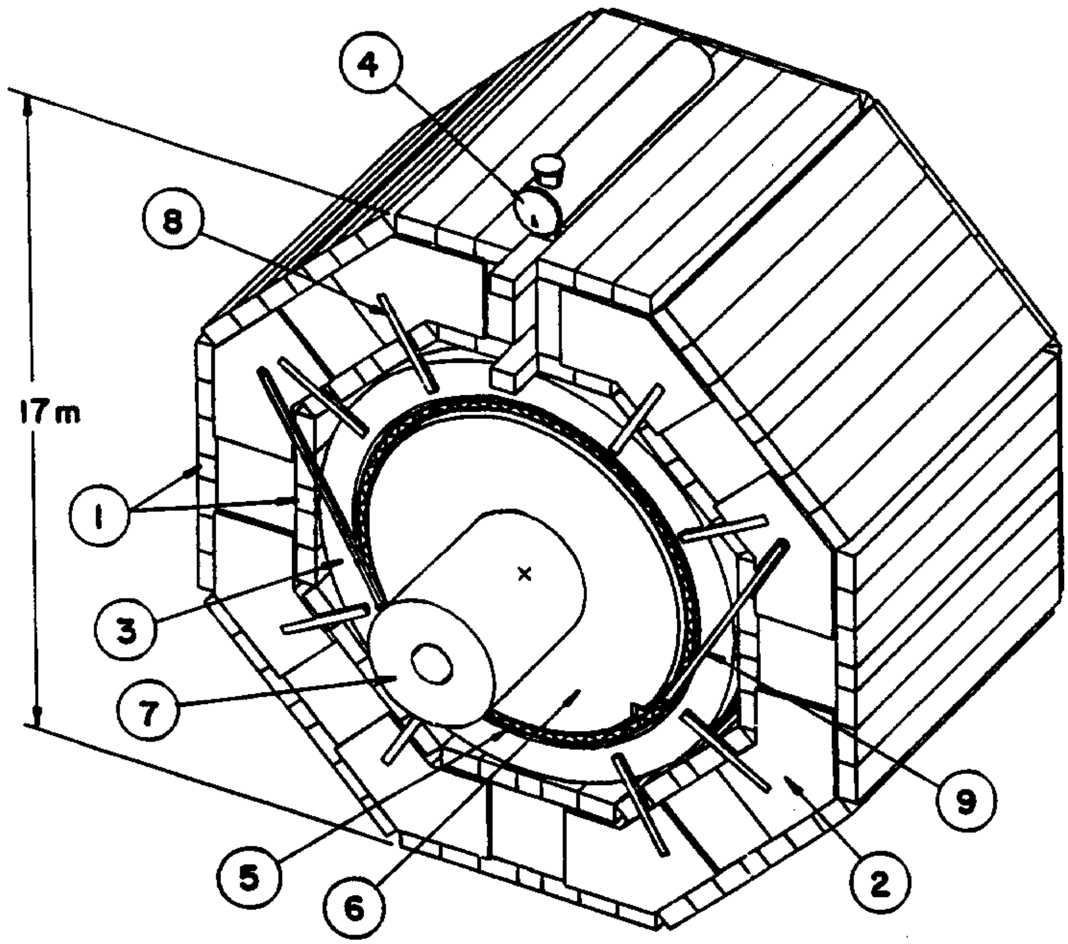

Figure 1. SSC Detector: 1, muon tracking; 2, flux return iron; 3, coil assembly; 4, 5000 L helium dewar; 5, calorimeter support structure; 6, calorimeter; 7, central tracking chambers; 8, coil supports; 9, support structure hangers.

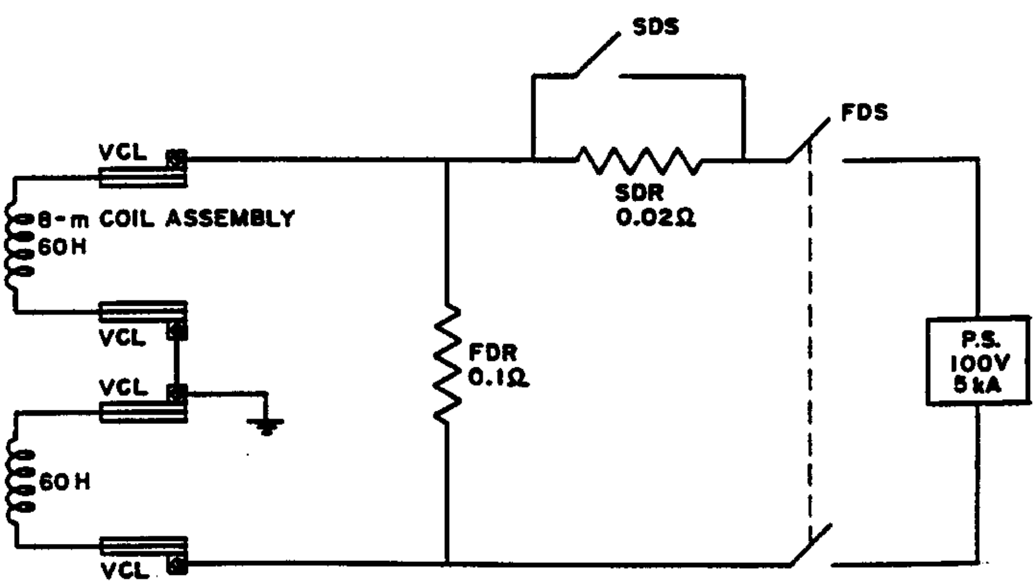

Figure 2. Electrical Schematic: FDR, fast dump resistor; FDS, fast dump switch (NC, open to initiate a fast dump); SDR, slow dump resistor; SDS, slow dump switch (NC, open to initiate a slow dump); VCL, vapor cooled leads; P.S., power supply.

Winding will be done with the coil axis vertical. The winding fixture will provide the radial preload and a series of compression bars at one end of each coil can be individually adjusted to provide a circumferentially uniform axial preload. These axial compression bars are adjustable only during assembly. After winding, the inner shell of the helium vessel will be welded to the coil form. After the four 2-m modules are bolted together and interconnections are made, the outer vacuum jacket and integral nitrogen shield are lowered over the 8-m cold mass. The coil supports will be attached, the 8-m assembly rotated to a horizontal position and the inner vacuum shell and nitrogen shield slid in. Figure 3 is a cross section of the coil, cryostat and vacuum vessel.

Supports

The axial body force on the 8-m cold mass is dependent on the geometry of the end wall and studied thus far, calculations indicate that this force, which is towards the symmetry plane, cannot be eliminated but is a minimum of 7.3 MN (1.64×10^6 lb) when there is no re-entrant iron. The supports are designed for an axial or radial misalignment, or the equivalent due to iron non-homogeneity, of 2.5 cm. The force constants are 8.8 MN/m (5×10^4 lb/in) for radial and 149 MN/m (8.5×10^5 lb/in) for axial misalignment. The supports to the cold mass have been chosen to be metallic and to have both a forced flow liquid nitrogen and a thermosiphon liquid helium intercept.

The supports for the cold mass can be either combined function or separated function with different elements to react the axial and radial forces. We initially favored a combined function support because by properly adjusting the angle of the support with the axial direction, the force due to thermal contraction could be eliminated, but, since these supports are at an angle to the axial direction, they generate a large radial buckling force while reacting the axial body and decentering forces. This disadvantage does not occur with a separated function support, and therefore we now favor this style. An additional advantage is that both elements of the separated function supports can be much longer and therefore greatly reduce the heat load.

The warm ends of all supports will be attached near the ends of the vacuum vessels to avoid transmitting the loads and weight through the shells. Both the axial and radial supports are located on the outer diameter of the helium vessel. The axial supports will have their cold ends connected near the inside bolted flange on the outboard 2-m module; whereas the cold ends of the radial supports will be attached near either end of the 8-m assembly.

Refrigeration and Cryogenics

The thermal shield cooling tubes and the support intercepts are fed with forced flow subcooled liquid nitrogen at an average temperature of 83 K. The inner and outer shields and each set of supports will have independent heat intercept circuits. The expected heat

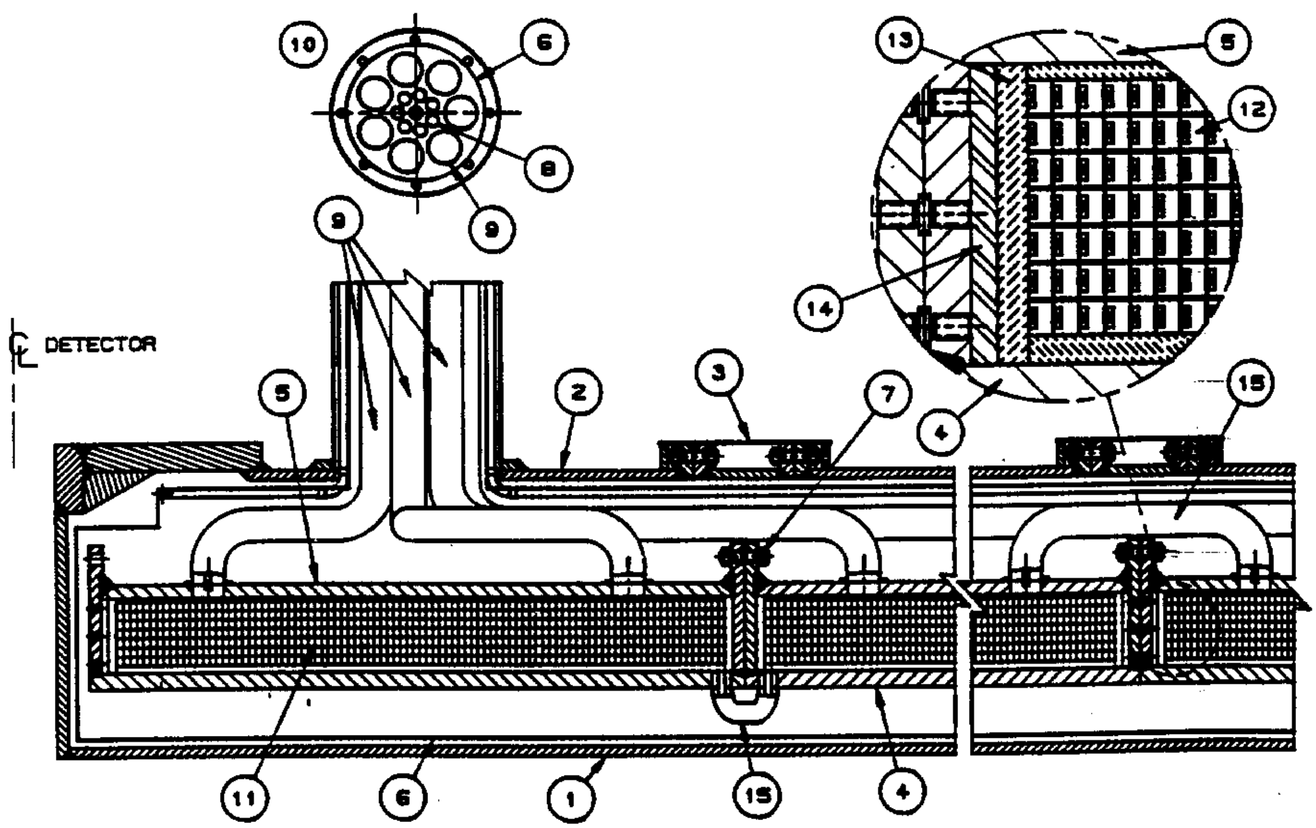

Figure 3. Axial cross section of coil, helium and vacuum vessels: 1, inner and 2, outer, vacuum shells; 3, assembly joint (if required); 4, inner and 5, outer helium vessel shell; 6, radiation shield; 7, coil module attachment; 8, liquid helium supply pipe; 9, helium return/vent pipe; 10, chimney to storage dewar; 11, coil winding; 12, conductor; 13, G-10 insulation; 14, axial preload bar; 15, electrical interconnect pipe.

load to the nitrogen system could be as much as 6 kW for the complete 16-m magnet.

A refrigerator at the surface supplies helium to two 5000-L storage dewars on top of the iron. A cold compressor will be used if needed to maintain the storage dewar at about 30 kPa and 4.5 K. Each dewar has supply and return lines to the four modules in one 8-m assembly. These lines are sized such that the return helium is less than 1% gas by weight and the supply lines are carefully insulated to ensure the maximum liquid fraction entering the bottom of the magnet. The steady state thermosiphon flow will be about 25 g/s to each module. Separate helium circuits, which will have a return flow of less than 7% by weight, will intercept the supports. The heat load from the separated function support system might be as high as 100 W depending upon the design. The total steady state heat load for the magnet system could be 410 W (230 W plus 36 L/h for lead flows). The 4.5 K refrigerator will have a capacity of 1600 to 1800 W.

In order to facilitate cooldown, a separate refrigerator would probably be employed. It would consist of a GHe/LN_2 heat exchanger and a turbo-expander which could provide 400 g/s of 55 K helium gas. This would be adequate to cool down the total cold mass (both 8-m sections) of 1000 tons in approximately two and a half weeks.

Conclusions

Preliminary work has indicated that the size and field requirements of this magnet are a reasonable extrapolation of existing superconducting magnet technology. The magnet design must be very conservative to guarantee high reliability, since the time to fix even a small problem could have a major impact on the SSC physics program. More detailed study must be done to optimize parameters both in terms of reliability and cost-effectiveness. Fabrication techniques must be examined more closely and the necessity of on-site construction must be rigorously evaluated. However, at this point, we see nothing that would preclude the construction of such a magnet.

Acknowledgements

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SSC DETECTOR SOLENOID DESIGN NOTE #31

TITLE: A Very Large Superconducting Solenoid *(Paper delivered by Bob Kephart at the 1989 International Industrial Symposium on the Super Collider, February 9, 1989, and accepted for publication in the proceedings.)*

AUTHOR: Bob Kephart et al

DATE: February 9, 1989

A VERY LARGE SUPERCONDUCTING SOLENOID

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ABSTRACT

A detector utilizing a superconducting solenoid is being discussed for the Superconducting Super Collider (SSC). A useful field volume of 8 m diameter x 16 m length at 1.5-2 T is required. The magnet will have a stored energy of ~1.5 GJ at 2T. All particle physics calorimetry will be inside the bore of the solenoid such that there is no need for the coil and cryostat to be "thin" in radiation lengths. An iron yoke will reduce the excitation required and will provide muon identification and a redundant momentum measurement of the muons. We have developed a conceptual design to meet these requirements. The magnet will use a copper-stabilized Nb-Ti conductor sized for a cryostable pool boiling heat flux of ~0.025 W/cm^2. A thermosiphon from a storage vessel above the cryostat will be used to prevent bubble stagnation in the liquid helium bath. The operating current, current density, coil subdivision and dump resistor have been chosen to guarantee that the coil will be undamaged should a quench occur. The axial electromagnetic force will be reacted by metallic support links; the stainless steel coil case will support the radial force. The 5000 metric tons of calorimetry will be supported from the iron yoke through a trussed cylindrical shell structure separate from the cryostat. The coil and case, radiation shield and stainless vacuum vessel would be fabricated and cryogenically tested as two 8-m sections. These would be lowered into the underground experimental hall and installed into the iron flux return yoke to provide the required 16-m length.

INTRODUCTION

The SSC will have six interaction regions located approximately 50 meters below grade. A large superconducting solenoid is being considered as a part of a detector facility for one of the interaction halls. Figure 1 schematically shows such an SSC detector. The calorimetry and central tracking chambers, which will be located inside the solenoid, require a field volume 8 m in diameter by 16 m long. The field in the bore is required to be 1.5-2.0 T; the field in the iron flux return yoke will be ~1.5 T. Locating the calorimetry internal to the solenoid eliminates the need to have a "thin" coil and cryostat in terms of radiation lengths. Because thickness is not a constraint, several coil types are possible. The design presented here is a cryostable pool boiling coil.

The required field volume will be provided by two solenoids, each 9.5 m in diameter and 8 m in length, connected in series electrically with a common power supply. Each 8-m unit will contain four identical 2-m long liquid helium/coil modules. The modules are mechanically connected and share a common vacuum vessel. Helium is supplied by thermosiphons to each module from a storage vessel located on top of the iron. Thus each module would have its own helium supply and return piping.

The calorimetry and flux return iron will be split at the longitudinal center and the halves can be moved independently; therefore, we will use two 8-m support structures to support the 5000 metric tons of calorimetry and central tracking chamber. There are notches in the iron for hangers for the supports and for instrumentation cables. The support structures are immediately inside the solenoids but are completely independent of the cryostat and vacuum shell. The ends of each structure will be supported from the iron. The support structures, consisting of concentric stainless steel cylinders with a trussed web, have a radial thickness of 25 cm and are expected to have a deflection of ~3 cm when loaded with the calorimetry. The calorimeter will rest on rails and can be inserted from either end.

QUENCH PROTECTION

Four 2-m modules are connected in series. The modules could in principle have separate gas cooled current leads. However, to reduce the overall heat load on the magnet, we assume that the modules in each 8-m section will be connected with superconducting bus in the liquid helium filled interconnecting pipes. It is essential that the coil survive quenches without damage and to this end a low current density and an external fast dump resistor were chosen. This resistor was chosen to be 0.1 Ω to limit the discharge voltage to 500 V across the terminals. The eddy current heating in both the coil and helium vessel during a fast dump is expected to be ~1300 W for an 8-m assembly. This might be sufficient to quench the coil and so the discharge will be through the fast dump resistor only if a normal zone is detected. The highest temperature reached in the coil due to a quench will be 100 K. A discharge for any other reason will be through a 0.02 Ω slow dump resistor with the power supply reversed to maintain a constant discharge voltage. The routine charge or discharge time, with 100 V across the terminals, would be 100 min and the eddy current heat load would be 26 W per 8-m assembly. Figure 2 is the electrical schematic.

CONDUCTOR AND COIL SPECIFICATIONS, WINDING AND ASSEMBLY SCHEME

The superconductor will be copper stabilized Nb-Ti wire which has a short sample current of 10 kA at 3 T and 4.5 K. This wire will be soldered into additional copper stabilizer. For the purpose of this study we assume the conductor will be 26 x 18 mm and will have a copper to superconductor area ratio of 146 to 1. Here we have chosen the stabilizer area to insure safe discharge of the coil in the event a normal region in the coil should develop. An operating current of 5000 A results in a current density of 1.56×10^5 A/cm^2 in the superconductor and 1068 A/cm^2 overall. The surface heat flux, with 25% wetting and a RRR of 100, is 0.025 W/cm^2.

There are seven conductor layers having a total of 651 turns in each 2-m coil module. Since the forces are radially outward, the coil will be wound starting with the outside layer, using the outer shell and flat annular heads as a coil form. Insulation will consist of G-10 buttons between turns, slotted G-10 sheets between layers and slotted G-10 and Kapton adjacent to the helium vessel. The packing factor will be 74% with 13% being helium space.

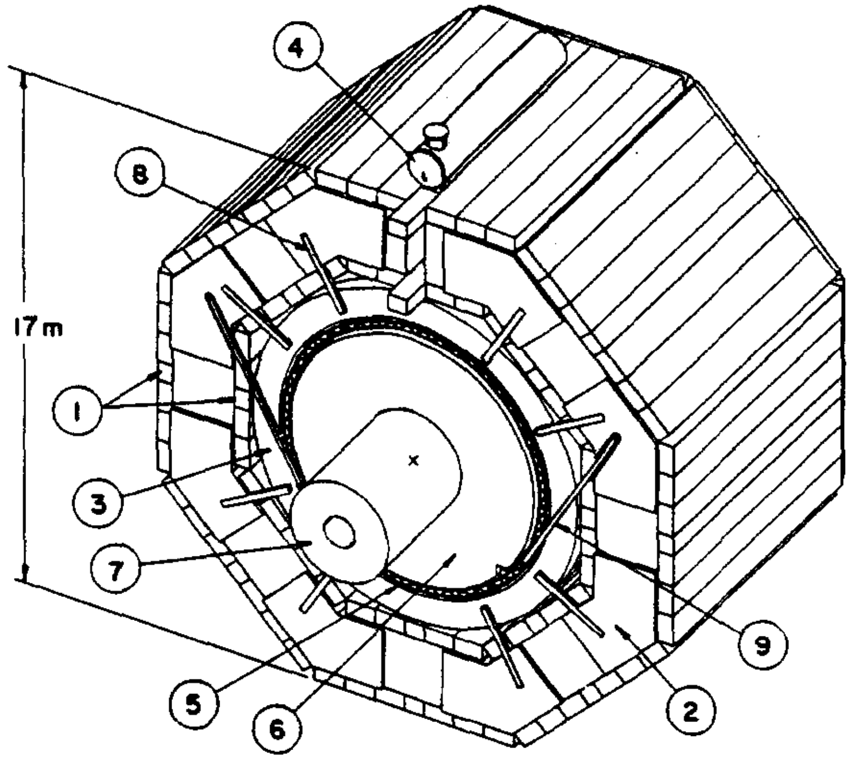

Fig. 1. One-half SSC Detector: 1, muon tracking; 2, flux return iron; 3, coil assembly; 4, 5000 L helium dewar; 5, calorimeter support structure; 6, calorimeter; 7, central tracking chambers; 8, coil supports; 9, support structure hangers.

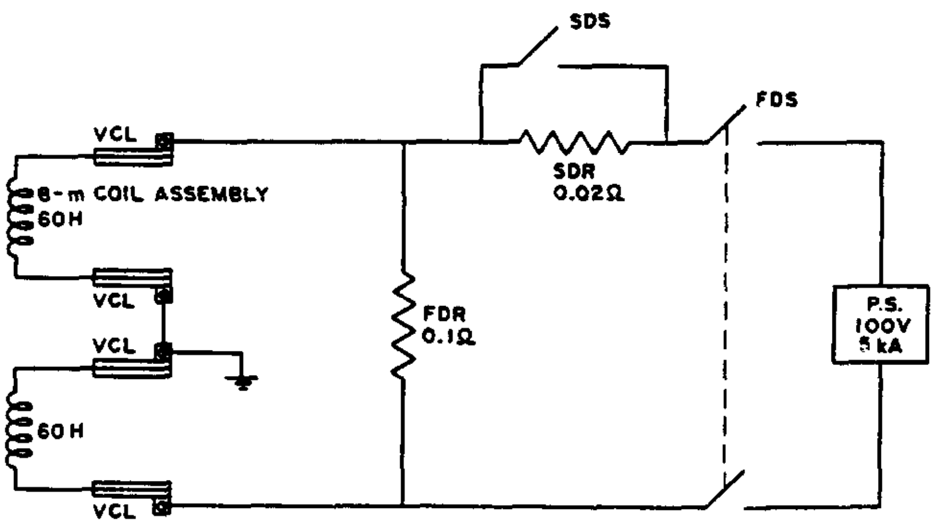

Fig. 2. Electrical Schematic: FDR, fast dump resistor; FDS, fast dump switch (NC, open to initiate a fast dump); SDR, slow dump resistor; SDS, slow dump switch (NC, open to initiate a slow dump); VCL, vapor cooled leads; P.S., power supply.

Each 2-m coil module will be designed in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code for an internal pressure differential of 0.8 MPa (116 psia) and will be adequately relieved for a loss of insulating vacuum or a quench of the coil. The axial electromagnetic force will be transmitted through the shells to the supports, and the radial force will be resisted by both the conductor and outer shell.

Winding will be done with the coil axis vertical. The winding fixture will provide the radial preload and a series of compression bars at one end of each coil can be individually adjusted to provide a circumferentially uniform axial preload. These axial compression bars are adjustable only during assembly. After winding, the inner shell of the helium vessel will be welded to the coil form. The four 2-m He vessels are bolted together. Each is located inside an inner and outer vacuum jacket and integral nitrogen shield. The entire 8-m cold mass is supported with respect to the magnet iron by separate metallic radial and axial supports. Figure 3 is a cross section of the coil, cryostat and vacuum vessel.

SUPPORTS

The axial body force on the 8-m cold mass is dependent on the geometry of the end wall. The supports are designed for an axial or radial misalignment, or the equivalent due to iron non-homogeneity, of 2.5 cm. The force constants are 8.8 MN/m (5 x 10^4 lb/in) for radial and 149 MN/m (8.5 x 10^5 lb/in) for axial misalignment. The supports to the cold mass have been chosen to be metallic and to have both a forced flow liquid nitrogen and a thermosiphon liquid helium intercept.

The supports for the cold mass are assumed to be separated function with different elements to react the axial and radial forces. We initially favored a combined function support because by properly adjusting the angle of the support with the axial direction, the force due to thermal contraction could be eliminated, but, since these supports are at an angle to the axial direction, they generate a large radial buckling force while reacting the axial body decentering forces. This disadvantage does not occur with a separated function support. An additional advantage is that both elements of the separated function supports can be much longer which greatly reduces the heat load.

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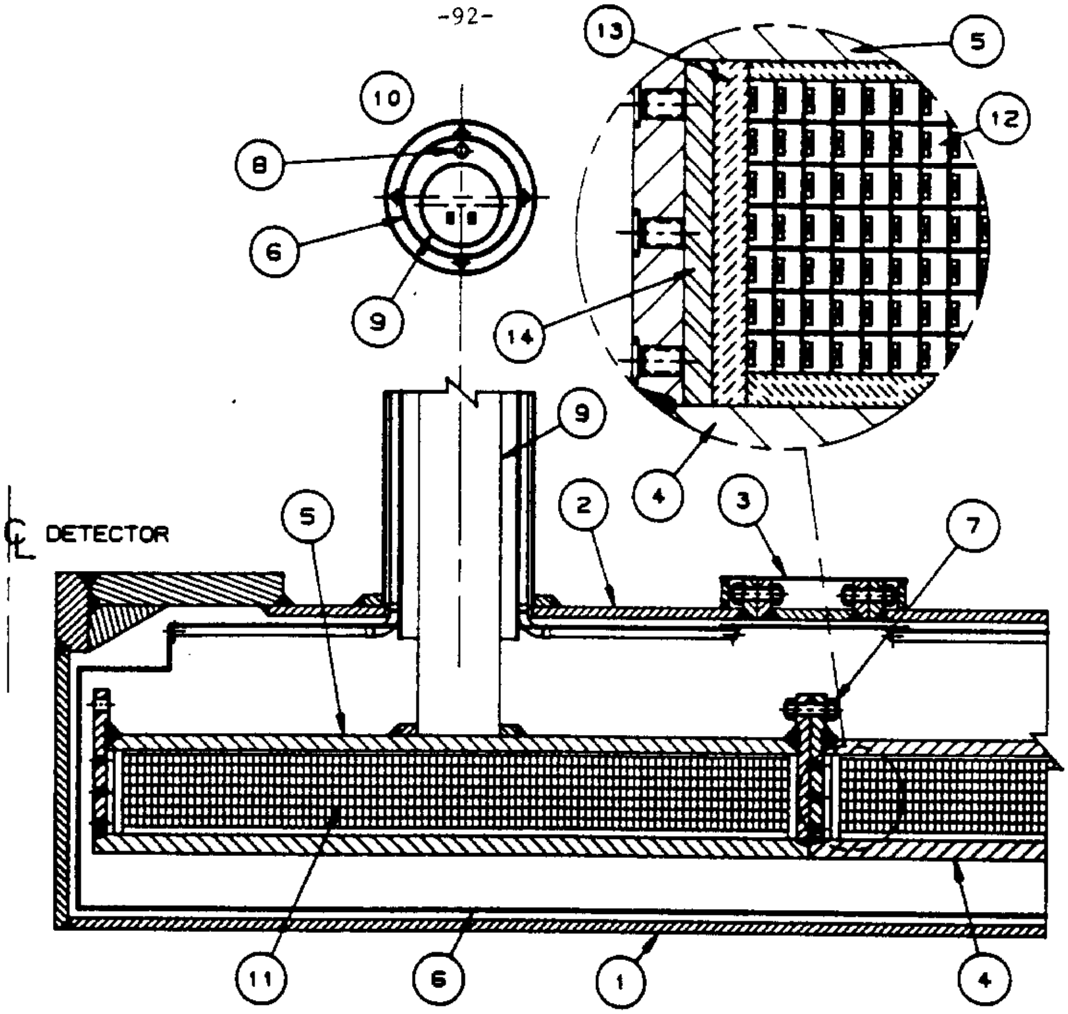

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ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Contract numbers DE-AC02-76CH03000 and DE-AC02-89ER40486.